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COMPOSITE RELIABILITY ENHANCEMENT VIA PRELOADING

by

Mark Christopher Jones

September 1988

Thesis Advisor: Edward M. Wu

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T239015

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5 MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION Naval Postgraduate School	6b. OFFICE SYMBOL (*If applicable*) 69	7a. NAME OF MONITORING ORGANIZATION Naval Postgraduate School
6c. ADDRESS (*City, State, and ZIP Code*) Monterey, CA 93943-5000		7b. ADDRESS (*City, State, and ZIP Code*) Monterey, CA 93943-5000
8a. NAME OF FUNDING / SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (*If applicable*)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (*City, State, and ZIP Code*)

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO.

11. TITLE (*Include Security Classification*)

COMPOSITE RELIABILITY ENHANCEMENT VIA PRELOADING

12. PERSONAL AUTHOR(S) Jones, Mark C

13a. TYPE OF REPORT	13b TIME COVERED	14. DATE OF REPORT (*Year, Month, Day*)	15 PAGE COUNT
Master's Thesis	FROM ______ TO ______	September 1988	156

16. SUPPLEMENTARY NOTATION The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Govt.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18 SUBJECT TERMS (*Continue on reverse if necessary and identify by block number*)

Composites, reliability, prestressing, preload, weibull strength distribution

19. ABSTRACT (*Continue on reverse if necessary and identify by block number*)

Composite strength is an inverse function of the size of the composite. As the use of composites expands into larger applications, such as airplane wings, missile components and ship superstructures the ability to accurately predict composite performance for large applications has become more important. The composite failure process is sequential and initiates with early breaking of the weak fibers. Concentration of breakage sites accumulate and lead to ultimately catastrophic failure. Prestressing fibers prior to solidification of the matrix has been demonstrated to increase the reliability of the composite by minimizing the spatial concentration of the breakage sights.

This study concentrates on quantifying the level of preload and gauge length to optimize the prestress effect. Computer simulations of graphite bundle tests were used to validiate actual AS-4 graphite bundle tests. The simulations were then extended to predict prestress performance.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL Professor Edward M. Wu	22b TELEPHONE (*Include Area Code*) 408 646-3459	22c OFFICE SYMBOL 67Wu

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted
All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

✩ U.S. Government Printing Office: 1986—606-243

UNCLASSIFIED

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Composite Reliability Enhancement Via Preloading

by

Mark Christopher Jones
Lieutenant, United States Navy
B.S.M.E., University of Michigan, 1980

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 1988

ABSTRACT

Composite strength is an inverse function of the size of the composite. As the use of composites expands into larger applications, such as airplane wings, missile components, and ship superstructures, the ability to accurately predict composite performance for large applications has become more important. The composite failure process is sequential and initiates with early breaking of the weak fibers. Concentration of breakage sites accumulates and leads to ultimately catastrophic failure. Prestressing fibers prior to solidification of the matrix has been demonstrated to increase the reliability of the composite by minimizing the spatial concentration of the breakage sights.

This study concentrates on quantifying the level of preload and gauge length to optimize the prestress effect. Computer simulations of graphite bundle tests were used to validate the data analysis methodologies applied to actual AS-4 graphite bundle tests. The actual experimental results are consistent with computer-simulated behaviors.

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ACKNOWLEDGMENTS

I would like to express my most sincere thanks and gratitude to Professor Edward M. Wu for his guidance and effort during the period I was fortunate enough to work with him in completing this thesis. He has been a teacher, a counselor, and an inspiration whose influence extends far beyond just the scope of this material.

I would like to thank Professor Gary Harlow for his assistance with the statistical analysis on the effect on fiber parameters due to prestressing and in modeling composite testing compliance.

I extend my appreciation to Mr. Jim Nagoette for his technical assistance and cooperation during the year.

I also would like to thank Lt. Joseph A. Schmidt for his assistance in the completion of this thesis. His assistance went far beyond computer programming, and without his enthusiasm and dedication this thesis might not have been completed.

I. INTRODUCTION

In the 1980s, the capability of military equipment has increased exponentially. Modern aircraft fly further and carry greater payloads, missiles have larger warheads and greater ranges, tanks have bigger guns and tougher armor, and ships have more capable but lighter weapon systems along with improved armor plating. Engineering improvements in the areas of electronics and composite materials have been on the leading edge of this technological revolution.

As reported in the fourteenth edition of *Ships and Aircraft of the U. S. Fleet*, the AV-8B Harrier II VSTOL attack aircraft "provides twice the payload of the AV-8A with up to 9200 lbs of external stores." The primary difference between the AV-8A and the AV-8B is the extensive use of composite materials in the wing and fuselage. This is just one example of the use of composite materials in existing military applications. New applications include the VS-22 Osprey tilt rotor aircraft, whose wing and fuselage will be entirely made of graphite epoxy composite material. Emerging "stealth" technology and its application to aircraft is a further new application of composites.

Composites offer designers many attractive features. These include very high strength-to-weight ratios, high stiffness-to-weight ratios, wear resistance, controllable heat expansion coefficients, corrosion resistance, fatigue resistance, low price, and ease of manufacturing and repairability. The field is expanding rapidly and research is bringing to the designer stronger, tougher, and stiffer materials every day.

A hurdle to be overcome for composites, however, is the general lack of understanding of the physics and mechanisms at work in the composite which give these materials their unique properties. This lack of understanding has restrained designers' ability to accurately predict composite strength. To compensate for this, large factors of safety are being used in the design of composite structures, which in turn adds weight and size and causes other related problems that reduce design efficiency. As the application of composite materials has expanded to larger and larger components, such as entire fuselages, rocket motor cases, and gun turrets, this problems has become magnified.

Composite materials are two or more dissimilar materials that when properly combined form a new material whose properties exceed either of the individual constituents. For the designer, composite materials provide an ability not only to optimize his design but also to optimize the material to be used for the design. Material properties of conventional materials that can be improved upon by using composites include stiffness, corrosion resistance, wear resistance, strength-to-weight ratio, and radar wave absorbability and reflectivity. Composites in use today include fiberglass, WEST (Wood Epoxy Saturation Technique), graphite-epoxy, Aramid-epoxy, and Boron-epoxy. Composite materials also include graphite-aluminum and hybrid composites of more than two constituents.

Commonly accepted types of composites are the *fibrous composites*, which consist of fibers in a matrix; *laminated composites*, which consist of layers of various materials; and *particulate composites*, which are composed of particles in a matrix. The composite is fabricated by combing the reinforcement material into a generally ductile matrix such as epoxy. This lay-up is called a *lamina*. Several layers of lamina may be combined in prescribed geometrical orientations to create a laminate. The designer specifies his materials and then designs the laminate to meet his requirements.

Until the early 1980s material properties of composites were predicted by a simple principle called the “rule of mixtures.” This approximation assumed that each constituent of the composite contributed to the overall composite property in direct proportion to its property weighted by its volume percentage in the composite. This linear weighting method was satisfactory for composite physical properties, which are *averaged* combinations of the constituent properties such as density and stiffness.

However, the “rule of mixture” is very inaccurate for those physical properties which are governed by extreme values such as permeation and strength. For such properties, considerable testing of a specific composite is needed to achieve representative material property values suitable for engineering design and reliability assurance. Not only are large amounts of data required for each specific composite but the designer’s material selections become limited to only those composites which have been tested. This characterization methodology could not keep up with the rapid pace of the introduction of new materials.

Clearly, a characterization method was needed to be able to *predict* composite material properties, particularly strength, if the full advantage of composites was to be obtained. Much work has been completed in the area by researchers such as Phoenix, Rosen, Harlow, and Wu. The most current papers on reliability and strength predictions of composites may be found in References 1, 2, 3, and 4. The most significant part of their efforts is that they have identified that the strength of composites is a probabilistic manifestation of the statistical strength of the fiber strength. The statistics of the fiber strength govern the number of failure sites in a composite. The probabilistic spatial distribution of the failure sites together with the failure mechanism govern the strength of a specific composite.

Different probabilistic models have evolved to capture the essence of the failure mechanisms. The simplest model is the "weakest link model," which envisions the entire composite as a long thin fiber; the entire chain (the composite) fails when the weakest link of the fiber fails. This model does not account for the redundancy provided by the matrix and as a result grossly underestimates the strength of the composite. The "equal load-sharing model" accounts for the redundancy provided by the matrix through definition of an effective length, an isolation parameter for the initial breaks. However, this model does not account for the stress concentration around the breaks and, as a result, over-predicts the composite strength. Finally, the "local load-sharing model" accounts for both the matrix redundancy and the local stress concentration. These refinements lead to the most realistic predictions to date.

There are two phenomena relating to the statistical strength of composites. The first is that the larger a composite becomes, the weaker it gets. The second phenomenon is that the larger a composite, the less strength scatter among such large structures. This is due to the the lower weak tail of the strength distributions of the constituent fibers. This effect has been demonstrated in the laboratory and in the field.

An extension of this theory then becomes that if the fibers are preloaded to break the weak sections of the fiber prior to their lay-up into the matrix, then the lower tail of the composite strength distribution is reduced and, in fact, becomes bounded by a value. This process is called prestressing. For a prescribed value, the strength and reliability of the composite may then be theoretically calculated for a given fiber and the magnitude of preload based on the modified fiber distribution. The variables to be determined to prestress a composite include the magnitude of the preload, the gauge length to which the load is applied, and the modified fiber parameters.

The ability to accurately recover the fiber strength parameters for small (less than 2.5 cm) gauge lengths is very important if the prestress effect is to be optimized. The bundle testing done in the laboratory yields data that includes not only the fiber data but also machine compliance, slack, and friction. For short gauge lengths, the contributions of slack and friction are small but compliance becomes relatively large. The portion of displacement contributed to by the experimental system compliance in a bundle test needs to be removed from the data if the true fiber parameters are to be obtained.

This study entailed the mathematical simulation modeling of strength prediction for a bundle of fibers with no matrix. This simulation was run on an IBM Personal Computer using Microsoft Fortran 4.01 for source code and Lotus 1-2-3 for graphing. When the simulation program had been validated, a zero gauge length bundle test was completed to measure the INSTRON fiber bundle testing machine compliance. A set of procedures was written to optimize a curve fit of the compliance data to provide an explicit equation which models the INSTRON system compliance.

When this procedure had been validated, bundle tests of varying lengths were tested at the Mechanics of Materials for Composites Laboratory at the Naval Postgraduate School. The displacement contributed to the test data by the INSTRON system compliance was removed from the total displacement. Under another thesis effort, this rectified data was analyzed in order to extract the fiber statistical strength distribution parameters.

The purpose of this investigation was to validate the experimental procedures and data analysis methods with the use of computer simulated data. Data generated from Monte Carlo simulation using known parameters is then utilized to assist in experimental design and the associated prediction theory. Experimental design and data interpretation methodology provide a proven foundation toward identification of an optimum gauge length for prestressing in order to *guarantee* the reliability of composite structures.

II. BACKGROUND

The tensile failure process of composite materials is a complex sequential combination of many different processes. These processes are controlled by the statistical strength of the fiber and the relative spatial clustering of the broken fiber sites within a composite. Given a probabilistic model which is capable of characterizing the sequential failure mechanisms, a formula can be derived to predict the probabilistic strength of the composite in terms of the statistical strength of the fiber. The parameters for such a probabilistic models can then be expressed in terms of other common measures of central tendencies (e.g., mean composite strength) and dispersions (e.g., strength scatter).

A. COMPOSITE STRENGTH PREDICTION

The prediction of the probabilistic strength of a composite as a function of fiber statistics was first introduced by B. W. Rosen in Reference 5, in the early sixties. He refined the simple weakest link model (which is essentially a series model) by accounting for the redundancy introduced by the presence of a matrix binder. The composite geometry he examined is shown below:

- a single layer of fibers
- evenly distributed throughout the matrix
- no fibers are in contact with other fibers
- the load is purely axial and in tension.

The strength of a single lamina of composite material is controlled by four factors:

- The strength and modulus distributions of the fiber.
- The strength and modulus distributions of the matrix.
- The interaction between the fiber and the matrix with respect to load sharing and stress concentration.
- The location distribution of relative strengths of the fibers with respect to the location distribution of relative strengths of the matrix.

When a composite is pulled in tension, because the fiber generally has a much higher modulus as compared to the matrix (e.g., graphite 10^8 Psi versus epoxy 10^4 psi), the fibers will carry most of the load. The load-carrying capability of the matrix can be neglected.

As the load is increased, each fiber will carry an equal amount of load that is equal to the applied load divided by the number of fibers.

$$P_f = P_t/n \tag{1}$$

The load on each fiber will be equal, but because the diameter of the fibers is not constant, the stress carried at each point in the fiber will be different. The stress will vary inversely to the diameter of the fiber. Some of the variations are regions of gradual thinning, others are indentations or nicks. These areas of reduced thickness or indentations or nicks are called “flaws.” These flaws reduce the load-carrying capability of the fiber by reducing its thickness and introducing stress concentration areas in the fiber.

A great deal of study has been done in identifying and quantifying the effect of these flaws on a microscopic scale. The work of Phoenix and Harlow proposed that on a macroscopic scale, if the flaws are distributed randomly with respect to location on the fibers and normally with respect to the severity of the flaw, then the strength of a fiber can be modeled as a long chain of segments. The strength of the segments may be modeled using the Weibull distribution. The model selection is expanded in Appendix A. The Weibull distribution is an appropriate model for the probability of failure of a chain with many links.

$$F(x) = 1 - \exp\,[-(x/\beta_x)^{\alpha}] \tag{2}$$

Where x = is the load applied to the fiber (the chain)

α = is the shape parameter characterizing the variability

β_x = is the scale parameter characterizing central location of the failure strengths.

The Weibull distribution for strength predicts the "size effect." That is, if the parameters are known for one given length, the parameters for any other lengths of the same material can be computed. This is also expanded in Appendix A.

As the load increases on the material, the stress on each segment of the fiber will increase as well. When the load reaches a point where the resulting stress is equal to the ultimate strength of a segment, that segment of fiber will break. This break will release a certain amount of strain energy into the composite. It will also cause an immediate local load concentration that will be felt by the adjacent and surrounding fibers.

The matrix, via its shear stress carrying capability, will attempt to absorb the released strain energy and distribute the local load concentration to the surrounding fibers. The actual values of the stress concentration factors caused by the fiber break are not known, but shear leg analysis yields reasonable approximations.

Once one fiber segment breaks, many events can occur. The first is that the matrix is strong enough to absorb the released strain energy and the surrounding fiber elements are capable of carrying the local load concentration. If this occurs, the material is stable and the load on each fiber will increase to

$$P_f = P_t/(1 - n) \tag{3}$$

Where n represents the number of broken fibers.

Another possibility is that the matrix can not absorb the released strain energy. In this case the matrix will split as it fails in shear. The material will continue to tear until its radius is such that the stress concentration decreases to a point below the ultimate strength of a section of the matrix. The fibers in this region will then be subjected to additional stress as the matrix pulls away. If the segments of the matrix are strong enough to carry the additional load, the material will then again become stable.

A further possibility is that the adjacent fiber segment may not be able to withstand the stress caused by the first fiber failure. In this case, that fiber segment will break and cause additional strain energy to be released. This reaction is called auto clustering. The process will continue until it is interrupted by a fiber segment that is strong enough to carry the stress or the entire piece fails catastrophically.

Some observations of the description above: The composite may fail due to either the local strength of the matrix or the local strength of the fiber or a combination of both. The likely initiation of the failure process will occur with a fiber break because the strength scatter or variance of the fiber is typically greater than that of the matrix giving rise to nucleation sites at already high stress regions. The chain of events that occur after that first break is dependent on the strength statistics of the adjoining matrix and fibers. If there are many strong segments surrounding a weak segment that fails, then additional material will not fail. If, however, this is not the case, then further damage occurs which may lead to final unstable catastrophic failure.

From the previously described failure process, it can be observed that the strength of the composite is dependent on the nucleating weak segments and the probability of there being another weak segment nearby. Therefore, the shape factor of the fiber strength distribution is the critical element that controls composite strength and reliability. Because of the mechanism of failure, as a composite becomes larger, the number of the population of fiber segments increases and the likelihood of the existence of very weak segments becomes larger. This causes the strength of the entire composite to decrease.

Another observation is that because the strength of the composite is controlled by the weak fiber segments, the strength may not be solved for explicitly because the actual value of the weak segments is probabilistic. The strength of adjoining segments is probabilistic, as well.

Prestressing solves two critical problems. First, it sets the lower limit of the strength of the segments by eliminating the weak segments by causing them to break prior to the application of matrix. Second, prestressing causes the weak segments to be broken without local load stress concentrations affecting the adjacent fibers and without the localized dynamic strain energy release because the weak segments are broken before the matrix is solidified. This results in auto clustering being minimized.

The critical implementation problem is then to find the "segment length" to ensure that the majority of the weak segments are eliminated and then determine a prestress level. The prestress level may be optimized to a level where the advantages of breaking the weak segments is balanced by the introduction of clusters to the matrix.

B. PRESTRESSING

G. J. Mills and associates, under an United States Air Force-sponsored project, conducted prestress tests on Boron fibers in the early 1970s. In his reports, documented in References 5, 6, and 7, he detailed how his work demonstrated the feasibility of the concept and provided data from early experiments that supported his expectations. His paper did not attempt to model or predict the effect of prestressing. He did note the effect of varying prestress gauge length and that as the gauge length decreased, the strength of the fiber increased, but he did not attempt to quantify an optimum length. He described the strength increase of the composite purely in terms of removal of weak segment and reducing the tail-end scatter of the fiber. He did not attempt to predict the performance of the composite once the matrix had been set. He did report that the strength did increase.

In 1986, Lt. David Bell and Professor E. Wu of the Naval Postgraduate School conducted prestress tests on AS-4 graphite/epoxy. The results are published in Reference 9. The report's experimental data confirmed the phenomenon of strength improvement after prestressing. This was in concurrence with Mills' laboratory data. Both papers accounted for the improvement by theorizing that the process of prestressing improved the strength of a composite because it reduced the strength scatter of the composite. The work done by Bell and Wu was only done with one gauge length, 10", and even with the problems encountered in handling the samples, the material did show a significant reduction in scatter and therefore an increase in the usable strength reliability.

Implementation of these findings to a practical application requires a model that can adequately predict the effect of prestressing as a function of prestress level, gauge length, and fiber strength parameters.

C. TESTING METHODS

There are two methods in which fiber strength statistics can be measured. One method is to prepare and perform a breaking strength test on one individual fibers. The second method is to form many fibers into a bundle of parallel fibers and then perform a controlled strain rate failure test.

The first method is very time consuming and error prone. The fibers are very thin (in the order of 10 µm) and handling requires delicate treatment. Laboratory conditions must be carefully monitored as the small fibers are susceptible to damage caused by temperature, wind, abrasion, and other disturbances. In addition, each test only provides one single point of data. If failure probability data is required down to .001 failure rate, then at least 10,000 samples should be tested.

Obviously, the second method is the preferred method. The bundle test, performed in our case on bundles of 1,000 filaments, will yield 1,000 data points with one test. The handling problems, while still present, are on a much more manageable level. The data analysis of the load vs. displacement data will yield the strength distribution parameters for the fiber that is equal to 1,000 individual filament tests.

It is important then that we measure the true load and displacement for just the fibers. The displacement that the testing machine measures is the sum of the fiber displacement, machine compliance, electronic noise, slack in the individual fibers, and friction between the fibers. Figure 1 demonstrates that test data is the combination of all of these factors.

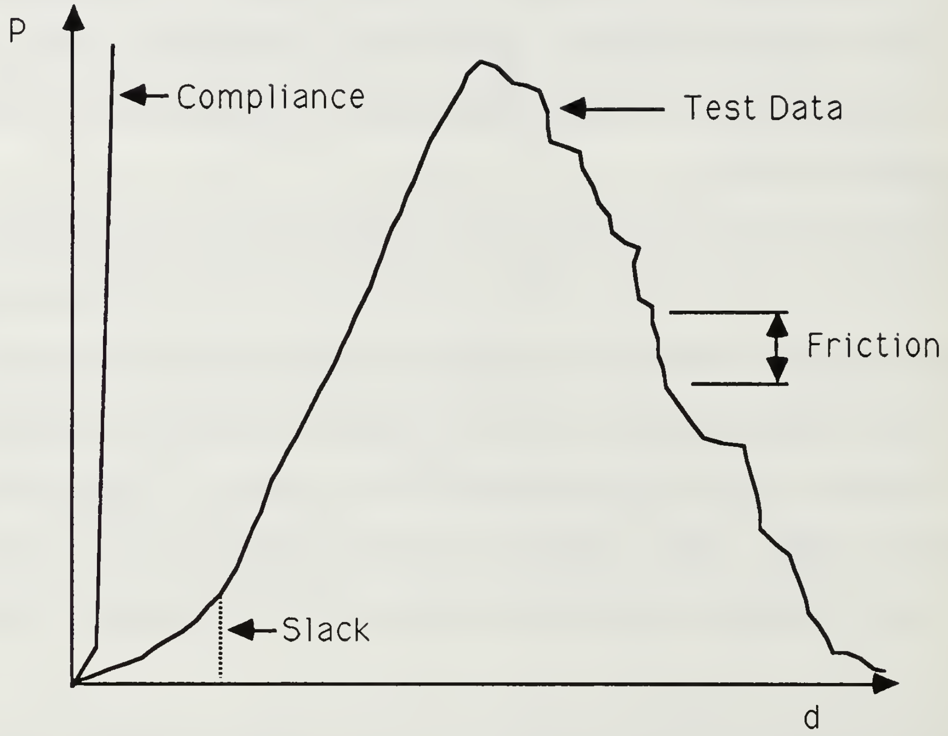


Figure 1

Typical Bundle Test Data Graph

The compliance is due to the mechanical construction of the testing machine. The machine operates with gears, clutches, and motors. Each of these has an initial start-up slip or backlash. The machine also has grips which hold the samples and the bases which will elongate under load. They are very stiff and the elongation is small when compared to the bundles, except when the bundle gauge length is short. This is illustrated in Figure 2, where the displacement is shown as percent strain. The compliance for the long sample has a greater slope than the short sample because the slope of the compliance in displacement multiplied is by the gauge length for percent strain.

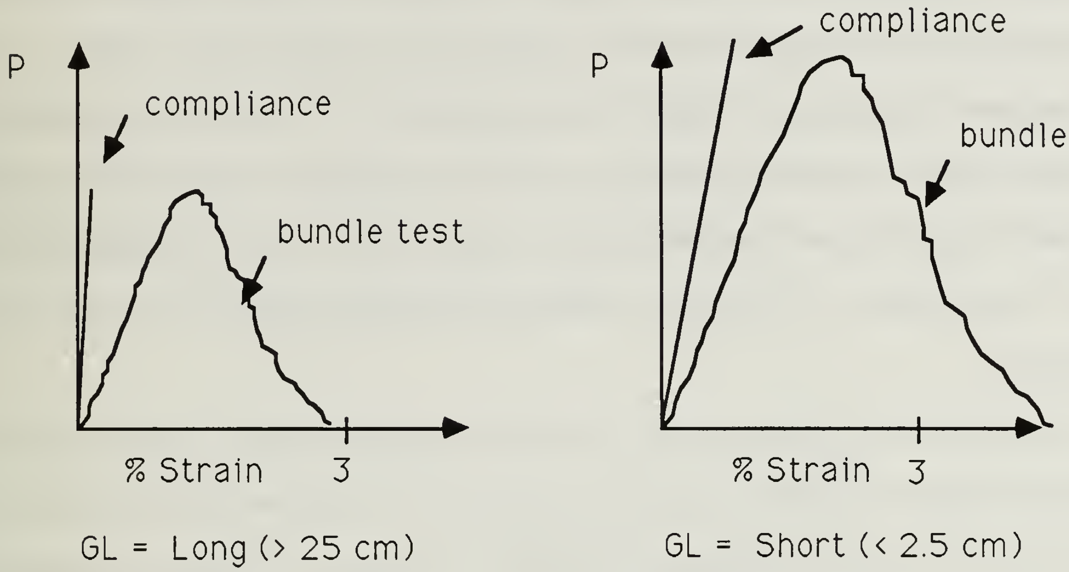


Figure 2

Effect of Compliance on Long-Gauge Length vs. Short-Gauge Length

The compliance of the machine can be measured if the there is no contribution to the displacement from the fibers. This is achieved using a zero gauge length sample. A sample must be utilized to include the sample grip mechanism in the compliance. A curve-fitting approximation is then applied to the data to create a continuous function of d in terms of P. This function may then be subtracted from the test data to eliminate the effect of compliance. This procedure and testing is expanded in Appendix C.

The effect of noise is sensed in the load cell. The sensitivity of the load cell is 1 out of 10,000. This is due to the limit of the analog-to-digital converter, which can only manage four bits of data. The amount of noise in the machine sensed by the load cell is very small when compared to the sensitivity of the load cell. As the load increase and the output changes in order of magnitude, the noise is not even noticeable. The noise in the machine is considered to be random electrical white noise due to interference in the data transmission lines. Observation of the data indicates that the noise is not very significant.

A simulation program was written during this study that allowed the user to input random noise up to any level. This will allow simulations to be run and investigate the effect of noise on the fiber strength parameters recovered from the simulated test.

The slack is due to the limitation of the sample preparation that all the fibers do not have exactly the same gauge length. This problem is found to be greater with the longer samples as compared to the short samples. The slack can not be eliminated by current sample preparation techniques, but extreme care by the technician in preparing the sample can minimize the effect.

Lt. Joseph Schmidt is examining the effects of slack on the calculated fiber parameters and expects to publish the results of his study in September 1988, from the Naval Postgraduate School, Monterey.

The effect of friction in the bundle test cannot not be definitively characterized. The presence of friction is manifested by large vertical drops in the load displacement curve, perhaps due to the tangling of broken fibers with unbroken fibers. The friction also will cause a fibers to break more than once. The effects of friction do increase with longer gauge lengths and are reduced with shorter gauge lengths.

With these factors that affect the data of the testing machine accounted for, the true fiber strength statistics may be recovered from the bundle tests. These statistics may then by used to optimize the prestress effect by calculating the effect prestressing will have in altering the fiber strength distribution.

III. PRESTRESSING MECHANISM

The prestressing process is to preload the composite fibers prior to solidification of the matrix to cause the weak segments of the fibers to break. The load that was carried by the broken filaments is then shared equally among the remaining fibers. Equal load sharing is in effect because the pre-solidified matrix cannot support a shear load and cause stress concentration cells to form. Upon solidification of the matrix, however, local load sharing is in effect, thereby increasing the local redundancy. Because the weak segments of the fibers were broken prior to solidification of the matrix, the local load concentration stress cells are not as severe as if the fibers had broken while in the matrix. The reduction in the severity of the stress concentration cells provides the reliability enhancement of the composite and is the motivation for prestressing.

The parameters that affect the prestress effect are gauge length, prestress magnitude, and the fiber strength distribution statistics. The optimum gauge length to prestress the fibers would be the ineffective length. The ineffective length, as described by Rosen in Reference 5, is a function of both the tensile strength of the fiber and of the shear strength of the matrix. This makes the ineffective length unique for each composite, and because both strengths are random variables, the ineffective length for a particular location in the composite is random as well.

As the gauge length increases, the likelihood of breaking all of the weak segments in the fiber decreases. This is because using the equivalent load sharing model, it is only possible to cause one break in each fiber over the gauge length. The break occurs at the weakest flaw, which may occur before reaching the desired prestress level. As illustrated in Figure 3, this allows other flaws weaker than the prestress level to remain unbroken.

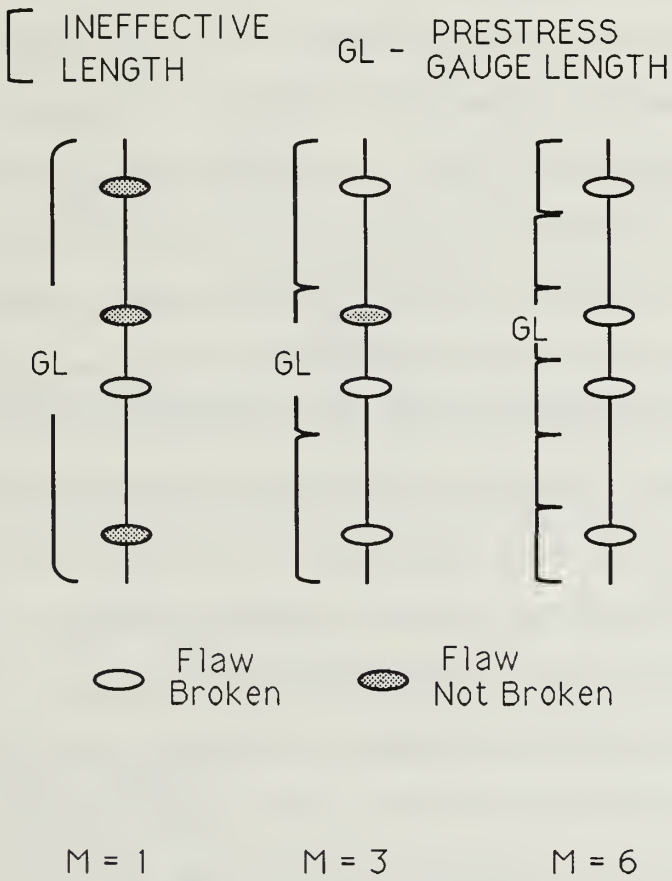


Figure 3

Effect of Preloading for Various Gauge Lengths

When the prestressed fiber is placed into a matrix, the local load-sharing model becomes applicable. With this model, the weak flaws in the composite will break under load and generate the larger stress concentration cells which prestressing is designed to minimize. The mathematical modeling of solving for the probability density function of remaining weak flaws given gauge lengths greater than the ineffective length and prestress levels is very complex. This problem is being treated in a separate project.

The preload level has two effects on the prestress effect. For higher prestress levels, more fiber breaks are introduced and more stress concentration cells will be created in the the composite once the matrix has solidified. The severity of the concentration cells is a function of the ineffective length. The shorter the ineffective length is, the smaller the stress concentration cell is because of less local load sharing. Second, the higher the preload level, the more difficult it becomes to grip or maintain the desired gauge length. The fibers by their nature have a small diameter, on the order of 5 microns for graphite, and are very susceptible to handling damage.

The underlying fiber statistics also have an effect on the prestress effect. The fiber strength variability (the Weibull model shape parameter α), has the greatest influence on the prestress effect. As seen in Figure 4 , if the shape parameter is very high ($\alpha > 20$), i.e., the fiber has low variability, then the prestress effect will not be very helpful. This is because the range of the distribution of the fiber strengths is very small and the weak tail that prestressing eliminates or reduces is inherently not present. Fibers of this strength uniformity, however, are not available at this time. If the shape parameter is small, then the scatter is much greater. With this scatter, the weak tail may be altered or removed by prestressing.

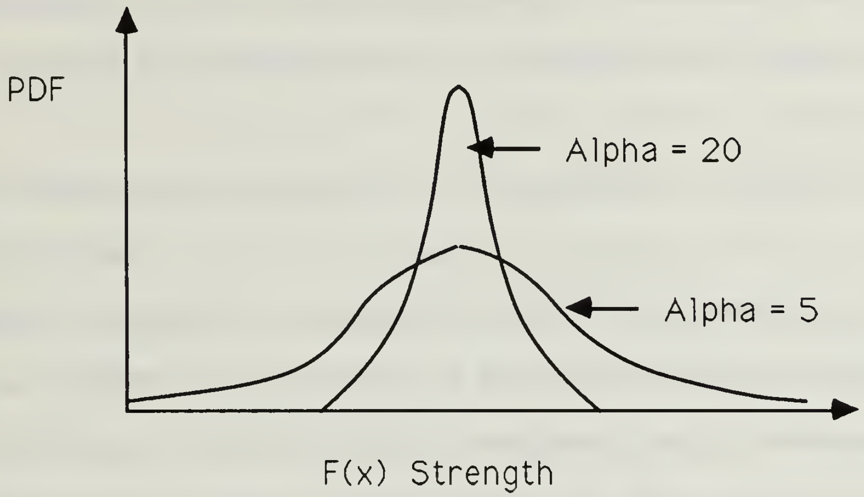


Figure 4

Strength Distribution for Fibers (Weibull Model)

The quantification of the prestressing effect can be written as a function.

$$PS = f(\Phi, \Psi, \alpha, \beta) \tag{4}$$

where Φ = Gauge Length
Ψ = Preload Level
α = Fiber shape parameter, Weibull
β = Fiber scale parameter, Weibull

The functional interrelation between these functions is presently not known and appropriate probabilistic modeling will be required.

One approach is to optimize each variable separately where possible. For example, the Weibull strength parameters characterize the fiber strength distribution. The prestress effect of the preload level and the gauge length will alter these parameters. The optimization of the effect on the alteration of these parameters on the reliability of the composite can be investigated as one means of optimizing the prestress effect.

The probability of failure (F*) vs normalized load (x*/β) graph for the fibers (F) and composite (C) with the Failure Probability Density Function superimposed is shown in Figure 5. This figure demonstrates how the PDF can be transposed to a linear curve. The linear curve is much easier to use and because it reveals in great clarity what is happening at the weak tail. This graph will be used to show the effect of prestressing with respect to failure probability.

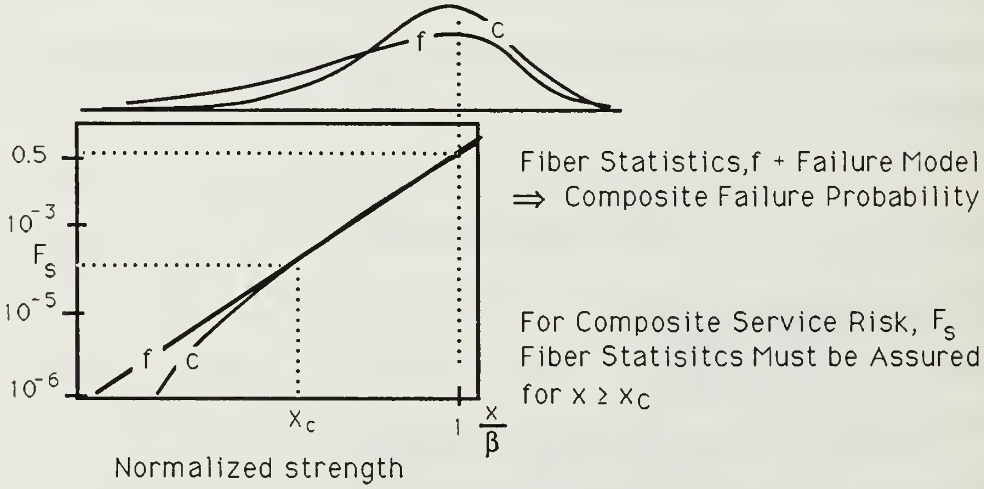


Figure 5

Probability of Failure vs. Normalized Strength

The probability of failure for the composite (C) is calculated from the fiber parameters. The composite reliability will diverge from the fiber reliability at X_c because of the local load-sharing stress-concentration cells. These cells cause the composite fibers in the matrix to break earlier because the fibers adjoining a broken fiber have to carry the load carried by broken fiber by themselves, not spread equally amongst all of the remaining fibers. Until the load X_c, the two curves do not diverge and the reliability of the composite is equal to the reliability of the fibers.

If the fibers have been damaged so that their distribution curve is modified to appear like that shown in Figure 6, the result on the composite strength can be seen. As the composite graph swings upward, its reliability is decreasing. The composite is stronger than the fiber due to the load sharing but its reliability for loads greater than X_c has diminished. The composite reliability for loads below X_c has not changed at all.

If the fibers' strength distribution could be improved, the failure probability curve would be shifted, as shown in Figure 7. The impact on the composite strength is that the curve swings downward. This downward swing reflects greatly increased reliability. In fact, the composite will not fail theoretically at all for any load less than X_c.

A method to achieve the fiber distribution in Figure 7 would be to proof test all of the composite fibers up to X_c and then remove any

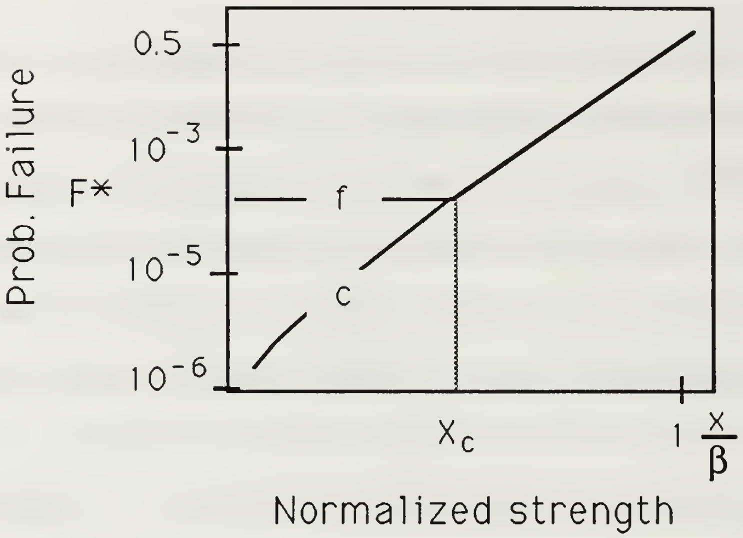


Figure 6

Probability of Failure vs. Normalized Strength (Damaged Fibers)

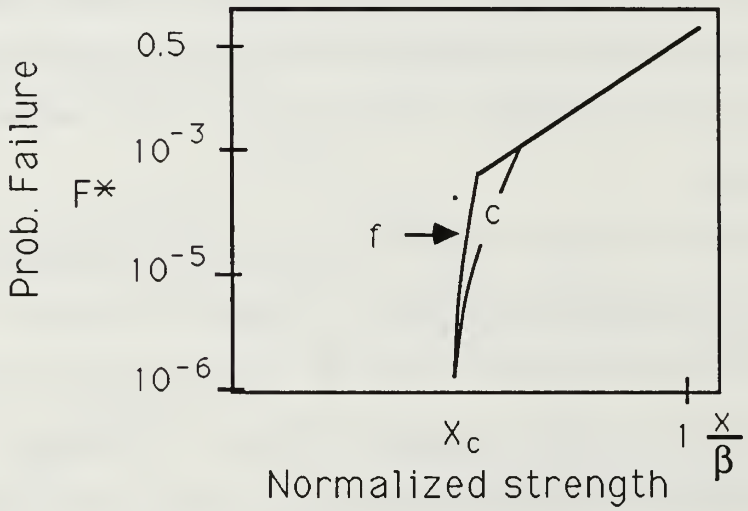


Figure 7

Probability of Failure vs. Normalized Strength (Improved Fibers)

broken fibers from the bundle prior to adding the matrix. The effect of this process on the failure probability curve is shown in Figure 8 as curve R. The cost of this operation, considering the extreme thinness of the fibers, the susceptibility to damage due to handling, and the extreme amount of fibers that make up the composite, make this process in reality impossible.

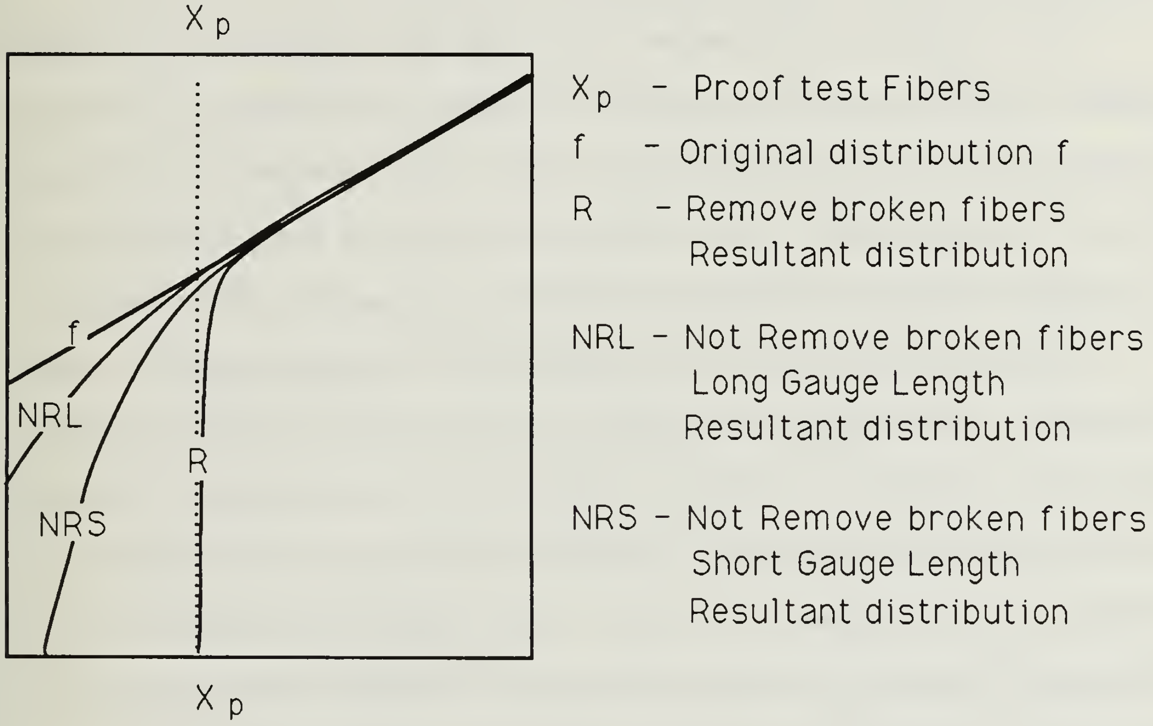


Figure 8

Effects on Failure Probability Curves Due to Proof Testing

Instead, what may be done is to preload the fibers to X_c on a gauge length equal to the ineffective length of the fiber. Because of the handling difficulties, the broken fibers will not be removed. The effect of this process on the failure probability curve is shown in Figure 8 as curve NRS.

The NRS curve has swung downward as compared to the original fiber curve, but it has not swung as far down as if the broken fibers had been removed. The reason it does not swing as far is the local load-sharing stress-concentration cells that are created when the matrix is added.

If the fibers are preloaded to X_c but on a gauge length that is greater than the ineffective length, the effect on the failure probability curve is shown on Figure 8 as curve NRL. This curve swings downward from the original fiber curve even less because of the probability that some fibers remain with segments that are weaker than the preload.

As previously stated, the strength of the composite may be calculated from the strength of the fibers. If the the fiber strength distributions are altered as shown in Figure 8, the composite strength distribution will be altered in the same direction as well. Using this, a designer of a composite may then use a failure probability curve to determine whether his design meets his reliability specifications. If it does not, he may then decide to improve the composite by prestressing the fibers to a critical load to alter the failure probability to come within the requirements.

The movement of the failure probability curve can be predicted by probability modeling based on the preload level, the gauge length, the ineffective length, and the original fiber strength parameters. The results of such an analysis (by Wu and Harlow) on the fiber swing for a fiber preloaded at the level 0.3 * β , for an α of 5.0 and prestressed at multiples of its ineffective length, are shown in Figure 9. The graph demonstrates that even if the prestress gauge length is very large compared to the ineffective length, significant improvement of fiber strength distribution can be achieved.

The optimization of the prestress effect is to identify the ineffective length or to find the shortest prestress gauge length that can be applied.

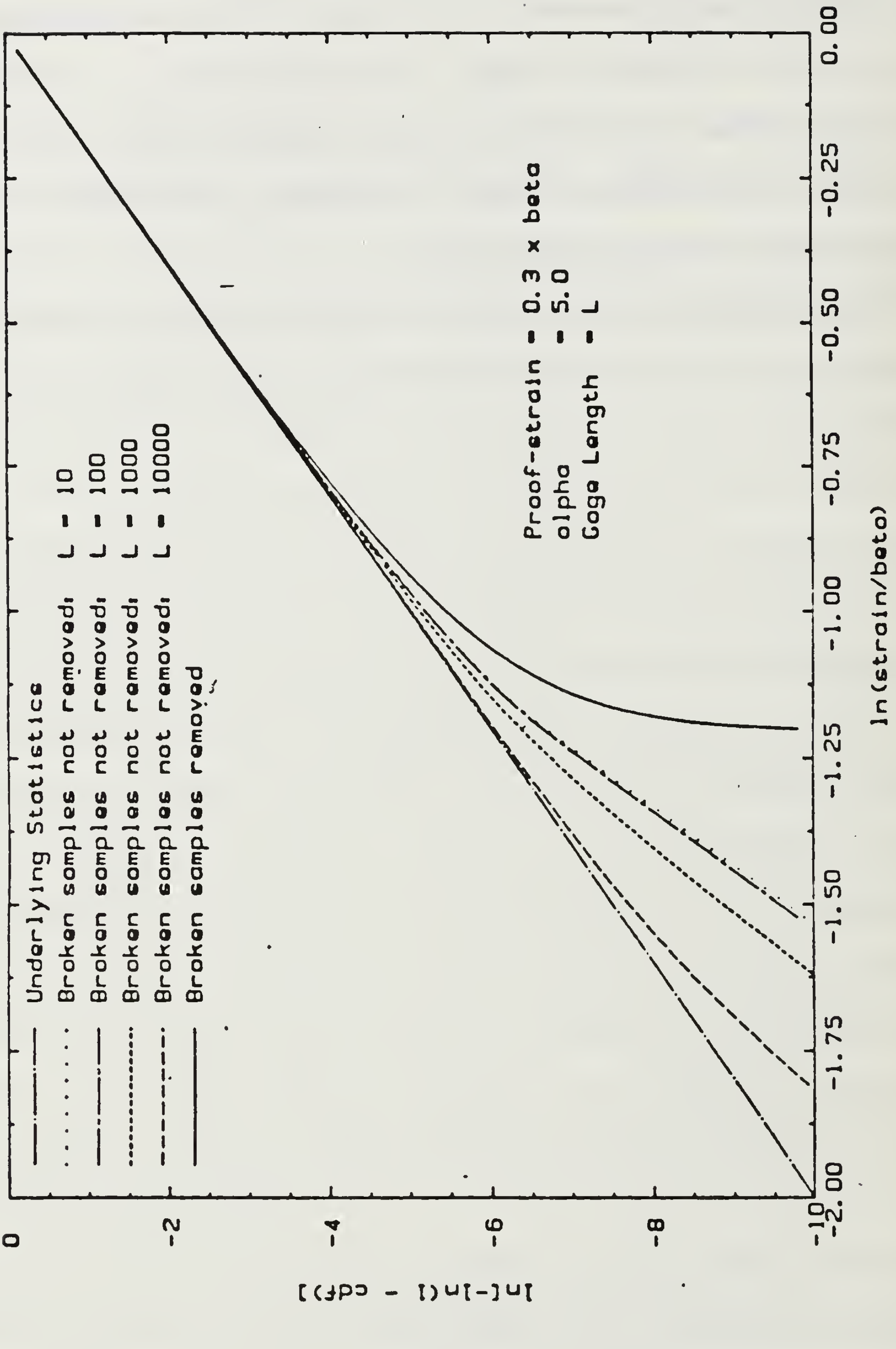


Figure 9

Probability of Failure vs. Normalized Strength Prestress Effect Simulation

IV. EXPERIMENTATION

The experimental work was directed in two areas. The first was to measure the machine compliance of the INSTRON 4206 (a universal materials testing machine) in order to characterize the testing machine system compliance denoted by the function δ_c (P). Once this was completed, the second portion of the experimentation was to perform failure tests on AS-4 Graphite bundle samples of various lengths in order to determine the strength characteristics and to observe the effects of gauge length on the test results with respect to compliance, slack, noise, and friction. Bundle samples were tested with no oil and then with oil in an attempt to reduce the effects of friction, particularly on the longer samples of 50 and 25 cm. Small-gauge lengths of 2.5 and 1 cm were tested with particular interest with respect to the examination of their suitability to preloading.

A. COMPLIANCE TESTING

The compliance testing was accomplished using a sample illustrated in Figure 10. The copper tabs were prepared and washed with a dilute acid to enhance the performance of the adhesive. The graphite bundle was glued to the lower set of copper tabs with acetylene adhesive. The upper tabs were then set so that the distance (d) between the the upper and lower tabs was as near zero as possible. The graphite bundle was then glued into place with the same adhesive. The sample was prepared by Composites Laboratory Technician, Jim Nageotte.

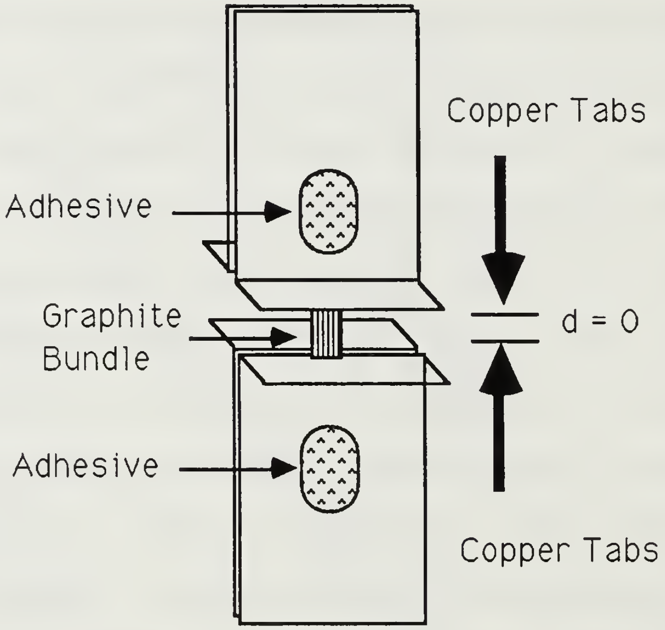


Figure 10

Compliance Test Sample

The tensile test was performed on the INSTRON 4206 testing machine and associated INSTRON software, version 4.01 . A plot of the load vs. displacement is shown as Figure 11. The data and test summary forms generated by the software are enclosed in Appendix E.

The compliance data was then fit to the function shown as Equation 4. This was done in accordance with the procedure for curve fitting detailed in Appendix C. The curve fitting was accomplished with the use of LOTUS 1-2-3 spreadsheet program and an IBM/AT. The resulting coefficients for the curve fit of the compliance are listed in Table I.

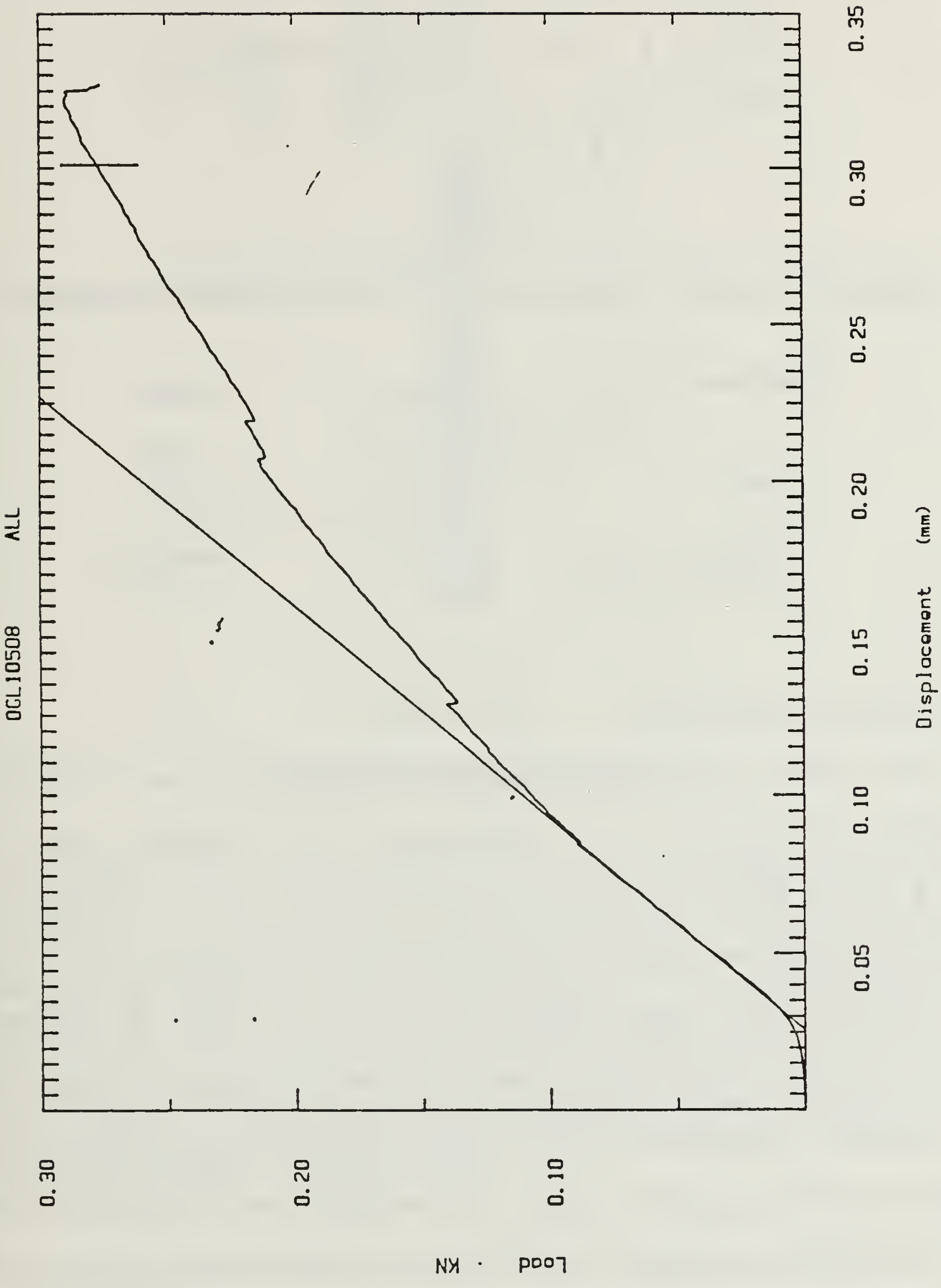


Figure 11

Compliance Test Load vs. Displacement Graph

INSTRON 4206 Compliance Curve Fit Function

$$\text{For } 0 < \delta < Dc1 \qquad \delta(P) = A_1(P)^n + A_2$$

$$\text{For } Dc1 < \delta \qquad \delta(P) = A_3(P) + A_4 \tag{4}$$

TABLE 1

INSTRON 4206 COMPLIANCE CURVE FIT COEFFICIENTS

Coefficient	Value	Units
A_1	.0512	mm
A_2	-.0217	mm
n	.1975	–
A_3	.0064	mm/kg
A_4	.0242	mm

B. BUNDLE TESTING

The bundle testing was accomplished with the use of samples as illustrated in Figure 12. The copper tabs were prepared and washed with a dilute acid to enhance the performance of the adhesive. The graphite bundle was glued to the lower set of copper tabs with acetylene adhesive. The upper tabs were then set so that the distance (d) between the the upper and lower tabs was the target gauge length. The graphite bundle was held straight with a 2 kg weight while the upper tabs were glued in place. The samples were carefully stored in the Composites Laboratory until use. As in the case of the compliance test sample, all of the samples tested were prepared by Laboratory Technician, Mr. Jim Nageotte.

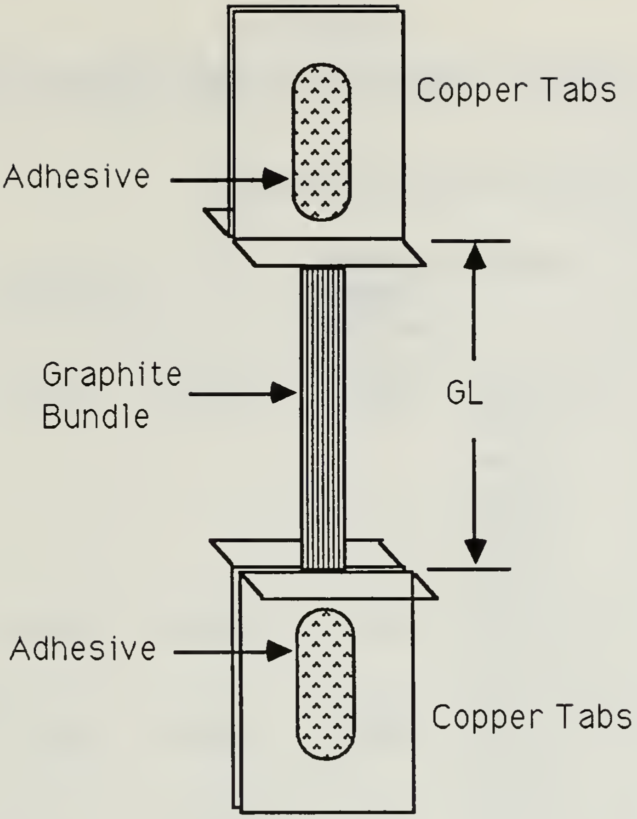


Figure 12

Graphite Bundle Sample

The bundle tests were performed on AS-4 Graphite bundles of 3,000 filaments. The tests were run in accordance with the procedure outlined in Appendix D. The displacement due to compliance was subtracted from the total displacement and a summary of the the results is listed in Table 2. The data and test summary forms generated by the software are enclosed in Appendix E.

TABLE 2

BUNDLE TESTING RESULTS (COMPLIANCE REMOVED)

Material: AS-4 Graphite (3000 filaments)

Test #	**Dry/ Oil**	**Gauge**	**Modulus Length (kg/mm)**	α	β (mm/mm)	**Comments**
090901	Dry	5.0 cm	1068	3.214	.0135	
090902	Dry	.5 cm				*
090903	Dry	.5 cm				*
090904	Dry	.5 cm				*
090905	Dry	.5 cm				*
090906	Dry	.5 cm				*
090907	Dry	5.0 cm				*
090908	Dry	5.0 cm	912	4.465	.0145	
090910	Dry	2.5 cm				*
080901	Oil	70.0 cm				Test Validation
100901	Dry	2.5 cm	915	3.000	.0157	
100902	Oil	2.5 cm				*
100903	Oil	2.5 cm				*
100904	Dry	50.0 cm	905	3.035	.0077	
100905	Oil	50.0 cm	959	3.660	.0085	
100906	Oil	50.0 cm				Not Analyzed
100907	Oil	25.0 cm	932	3.964	.0101	
100908	Dry	25.0 cm	917	3.180	.0097	

* Adhesive Failure

Examination of the load vs. percentage strain plots revealed the fact that for the shorter gauge lengths, 2.5 and 1 cm, the copper tabs failed to grip the graphite bundle uniformly. This caused some of the fibers to slip out of the tabs and the data from these tests were of no validity. The tests that had this phenomena are listed as adhesive failure in the comments section of Table 2. Figure 13 shows a representative example of this phenomenon as the load remains constant while the percent strain increases beyond the limit of the experiment.

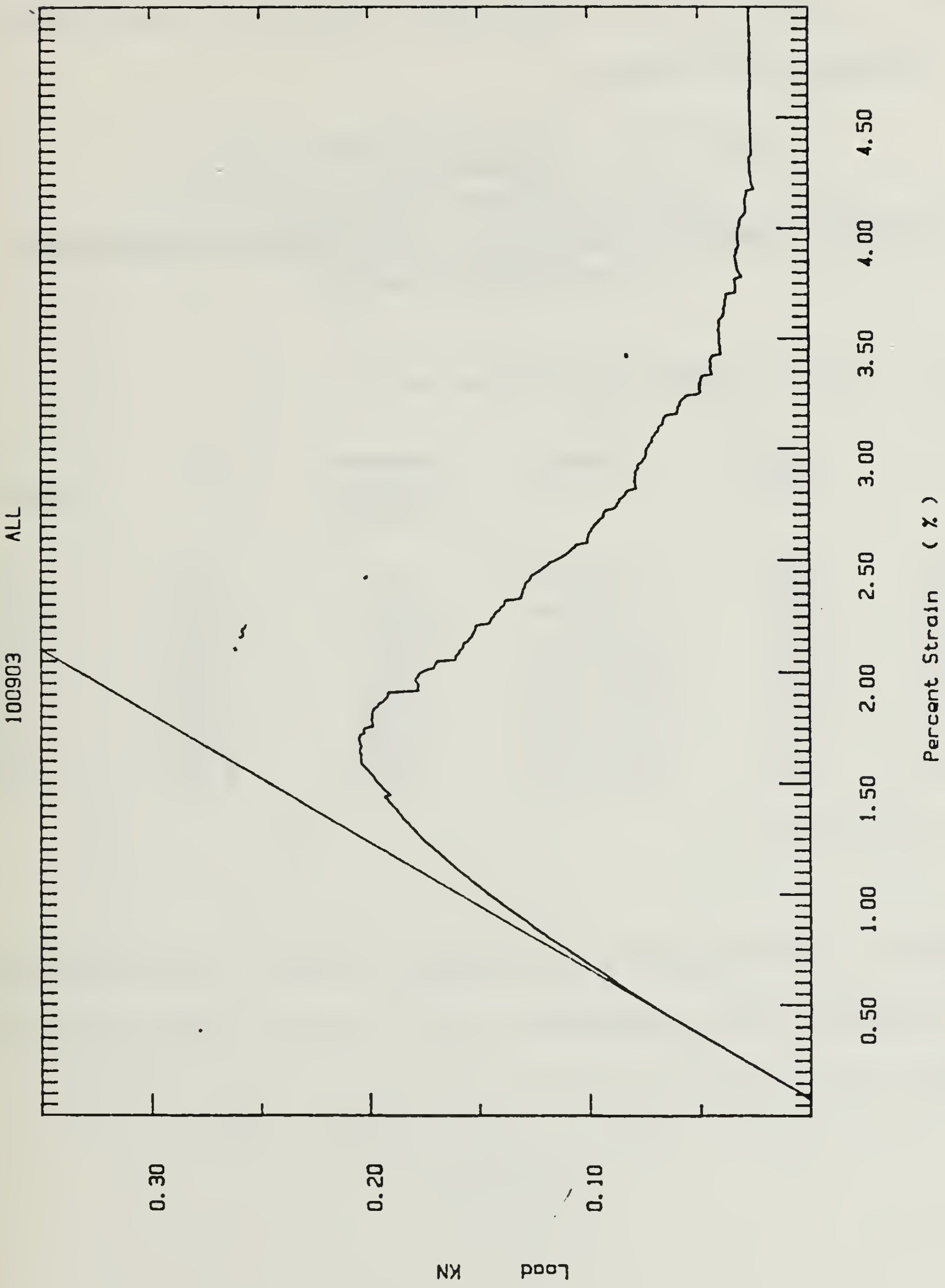


Figure 13

Load vs. Percent Strain for Sample 100903 (Adhesive Failure)

An examination of Table 2 shows that seven of the 18 samples resulted in satisfactory tests. The seven successful tests results have been summarized into Table 3.

TABLE 3

BUNDLE TESTING RESULTS (COMPLIANCE REMOVED) SUCCESSFUL TESTS

Material: AS-4 Graphite (3000 filaments)

Test #	**Dry/ Oil**	**Gauge**	**Modulus Length (kg/mm)**	α	β **(mm/mm)**
100901	Dry	2.5 cm	915	3.000	.0157
090901	Dry	5.0 cm	1068	3.214	.0135
090908	Dry	5.0 cm	912	4.465	.0145*
100908	Dry	25.0 cm	917	3.180	.0097
100907	Oil	25.0 cm	932	3.964	.0101
100904	Dry	50.0 cm	905	3.035	.0077
100905	Oil	50.0 cm	959	3.660	.0085

* Data not plotted

Figures 14 through 32 are the graphs of load vs. percent strain of the test data, of the compliance, and of the test data with the fiber removed.

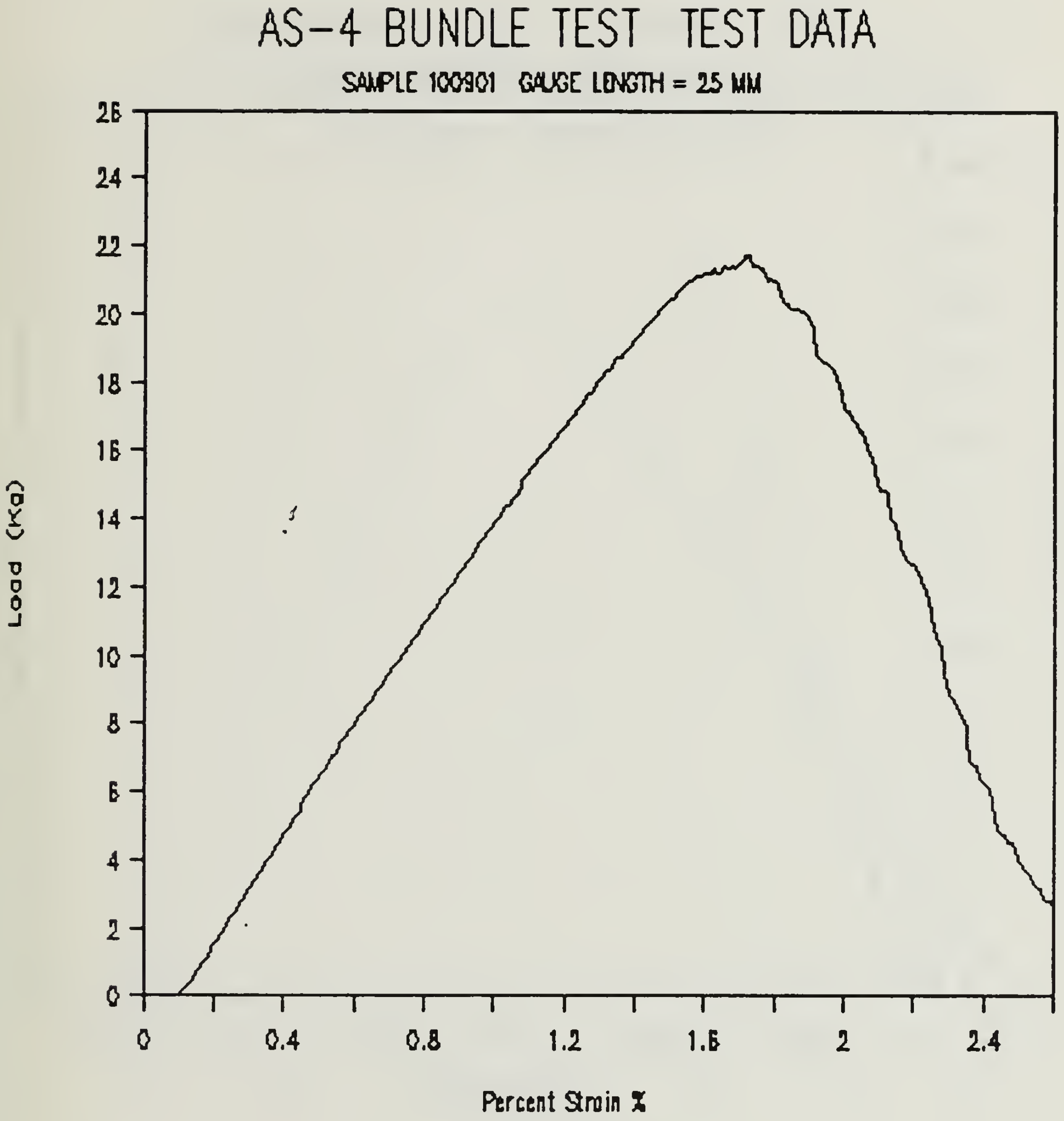


Figure 14

Load vs. Percent Strain Sample 100901 Test Data

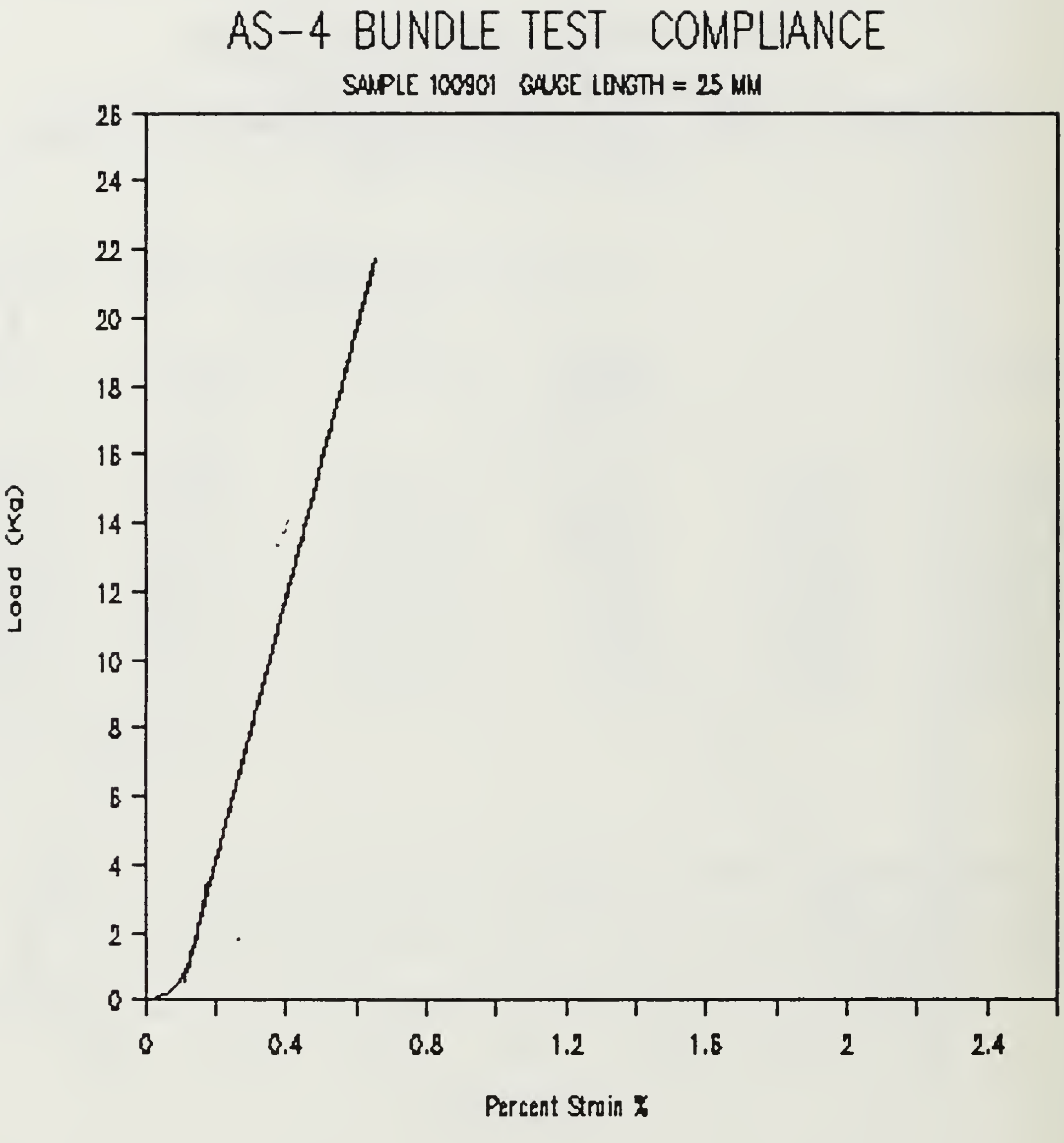


Figure 15

Load vs. Percent Strain Sample 100901 Compliance

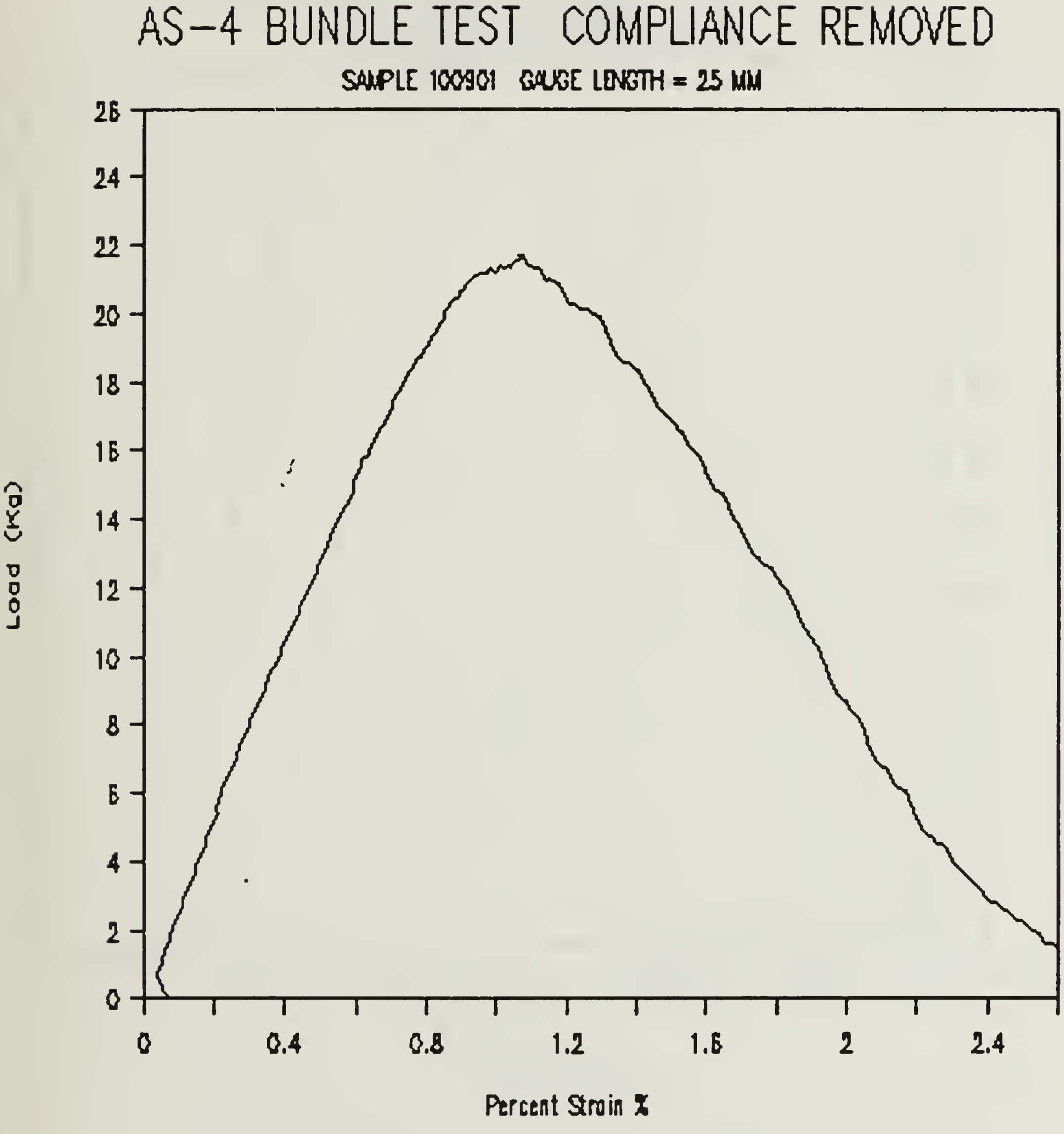


Figure 16

Load vs. Percent Strain Sample 100901 Compliance Removed

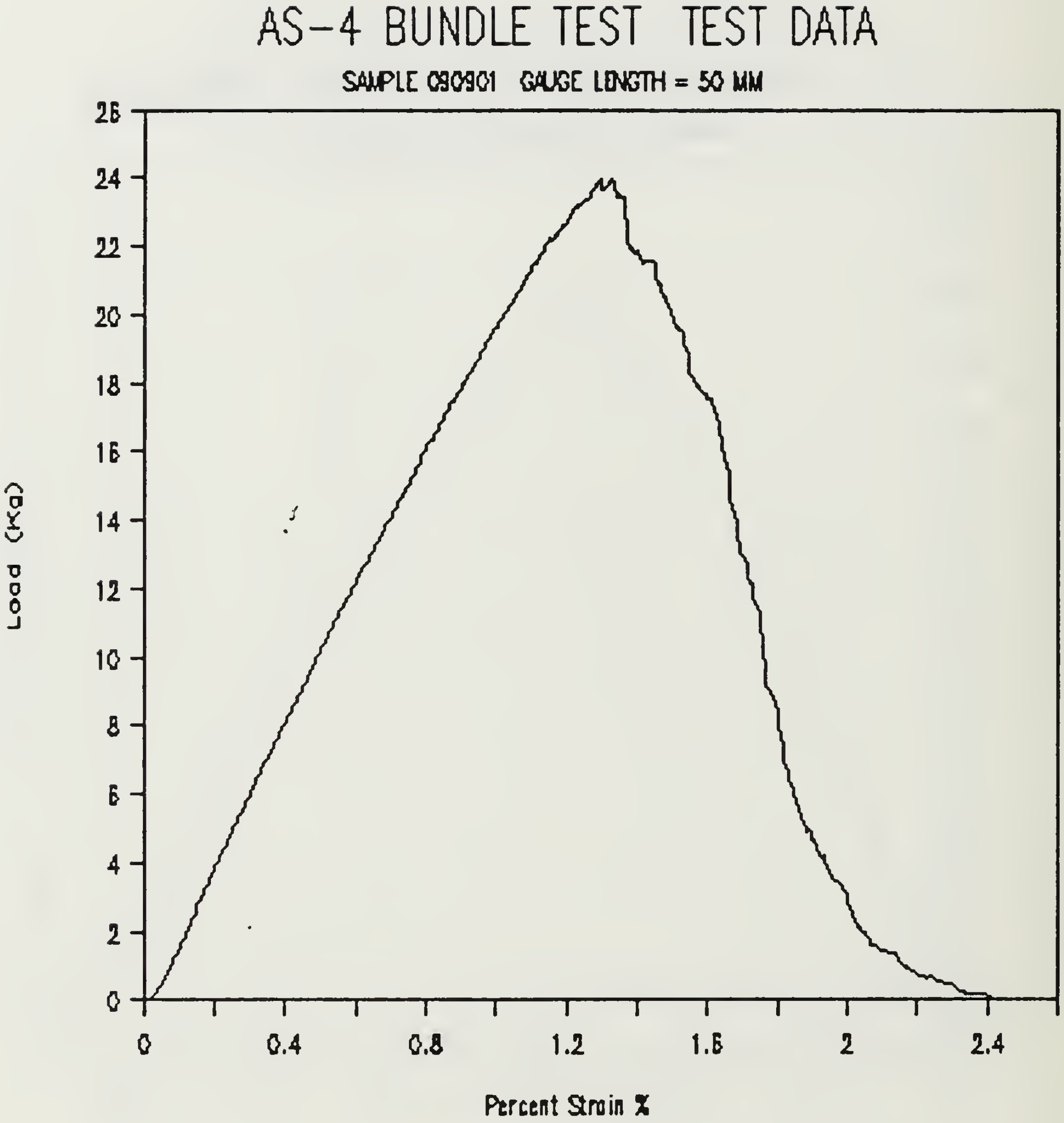


Figure 17

Load vs. Percent Strain Sample 090901 Test Data

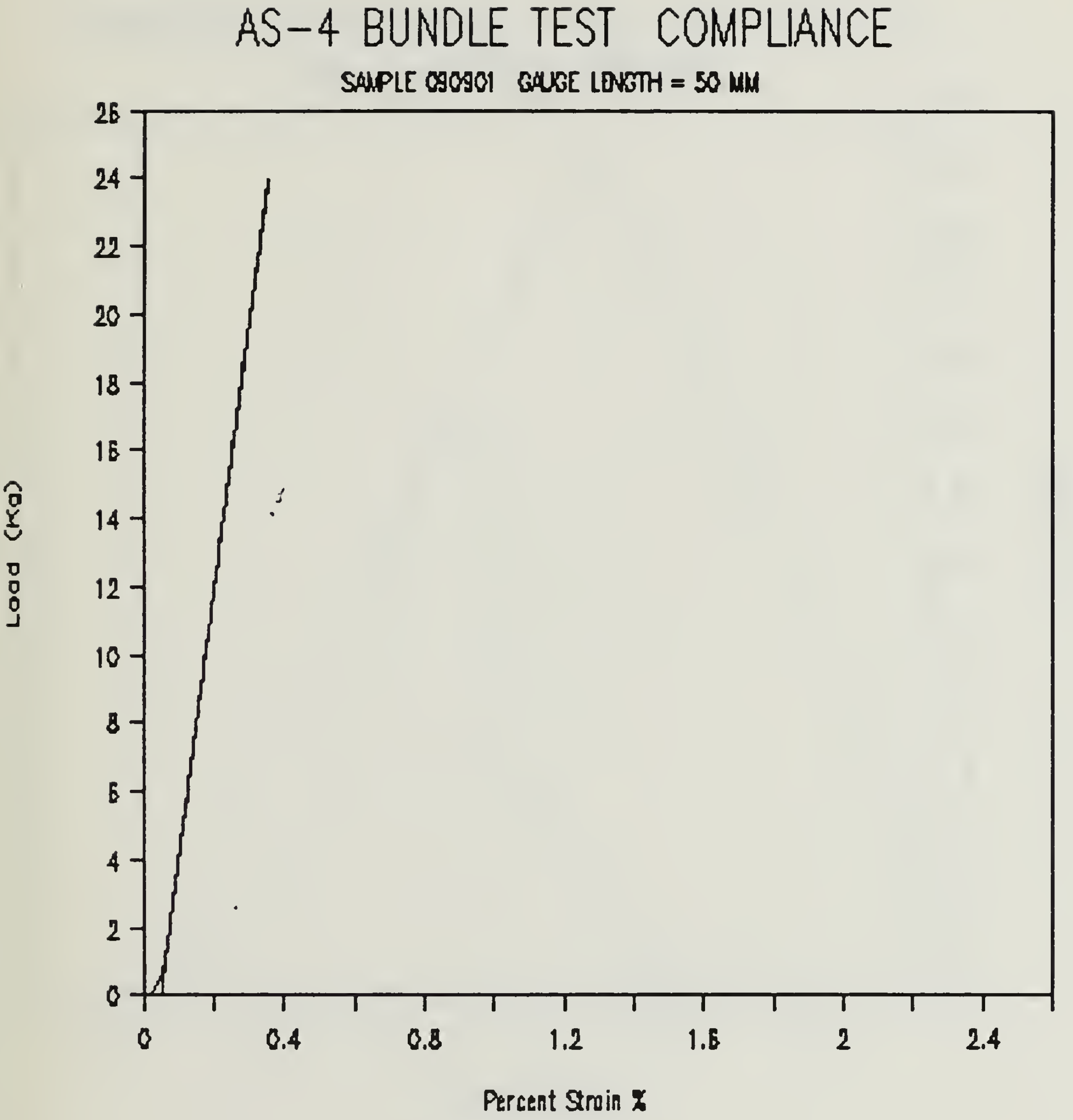


Figure 18

Load vs. Percent Strain Sample 090901 Compliance

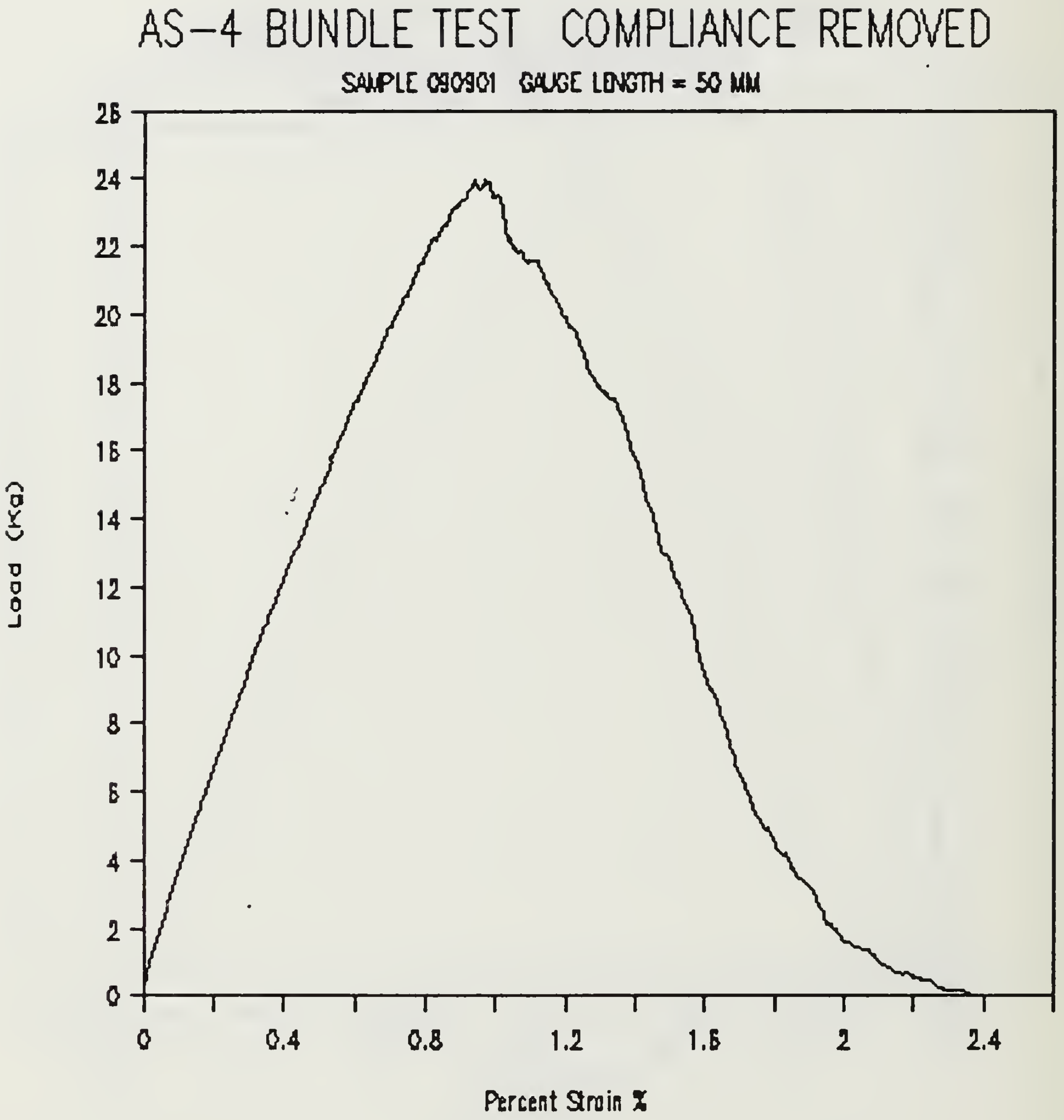


Figure 19

Load vs. Percent Strain Sample 090901 Compliance Removed

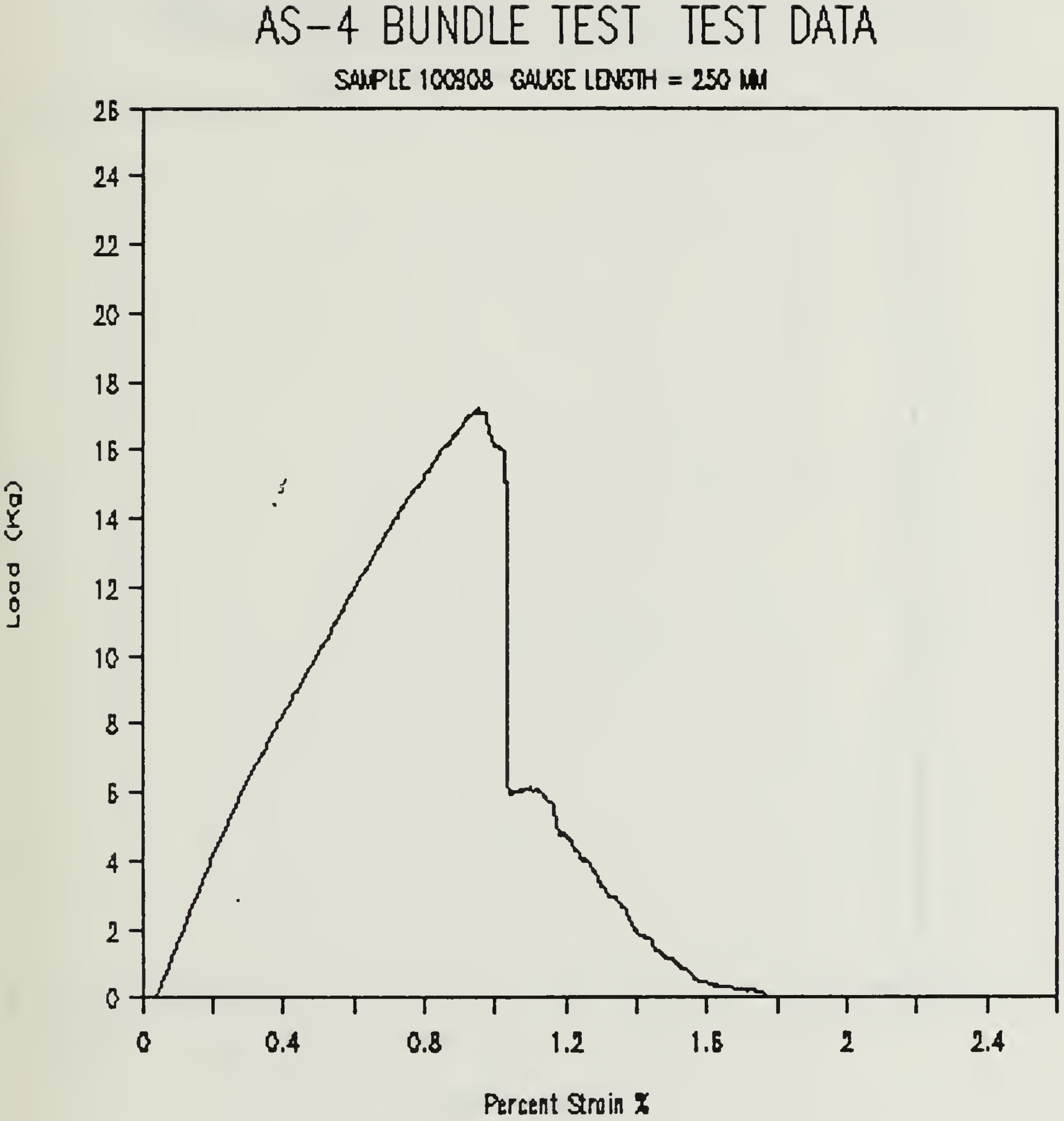


Figure 20

Load vs. Percent Strain Sample 100908 Test Data

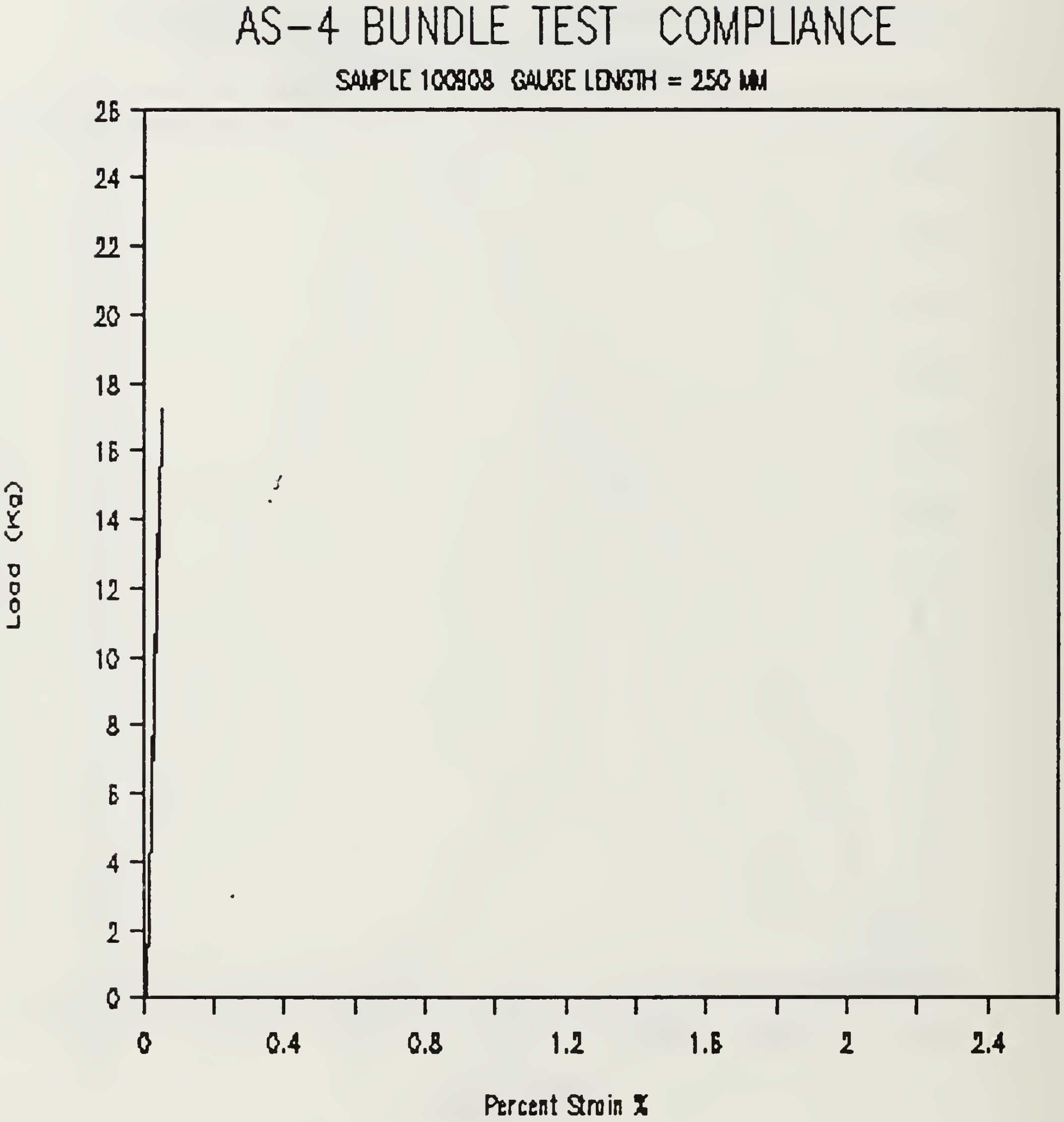


Figure 21

Load vs. Percent Strain Sample 100908 Compliance

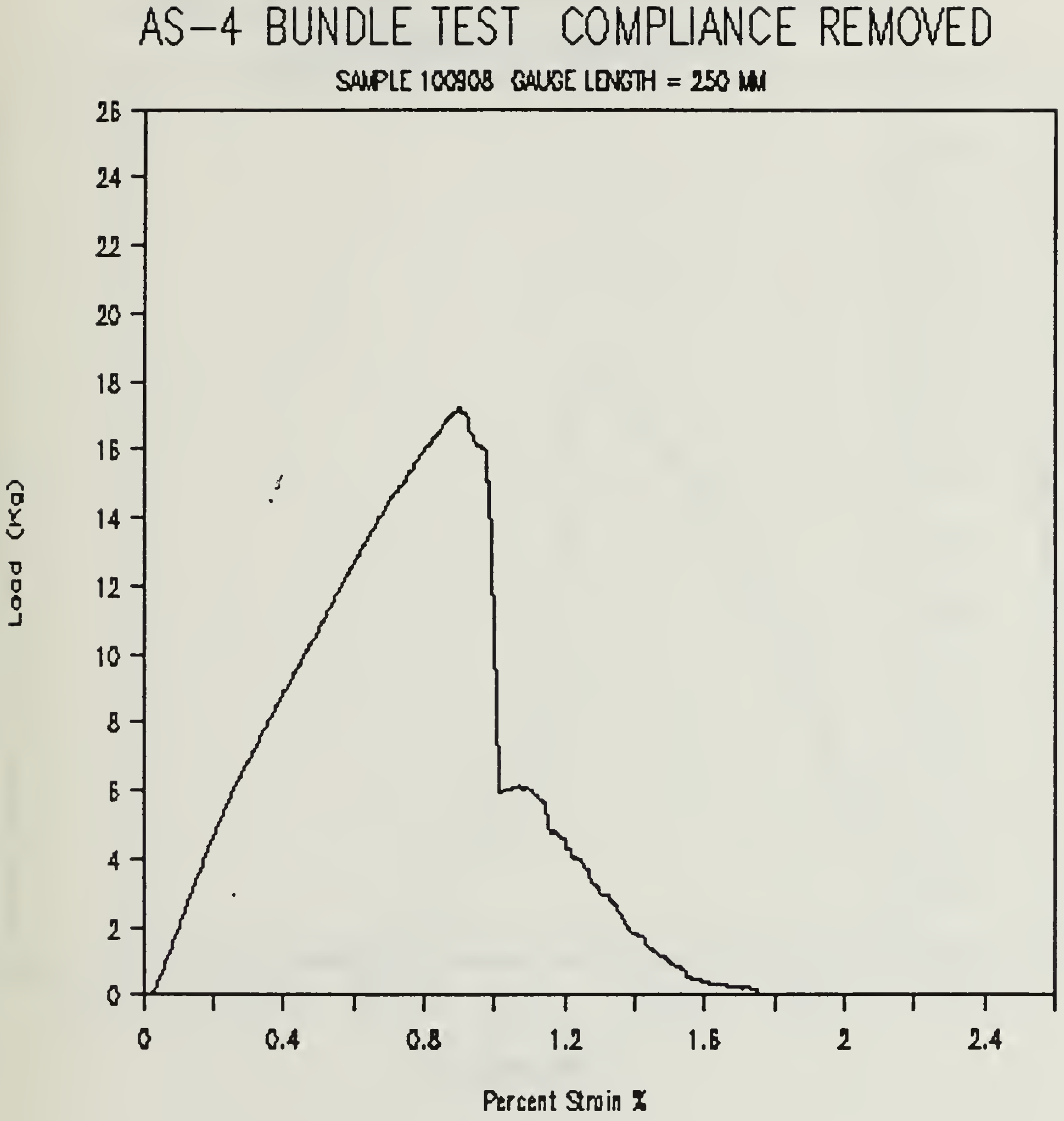


Figure 22

Load vs. Percent Strain Sample 100908 Compliance Removed

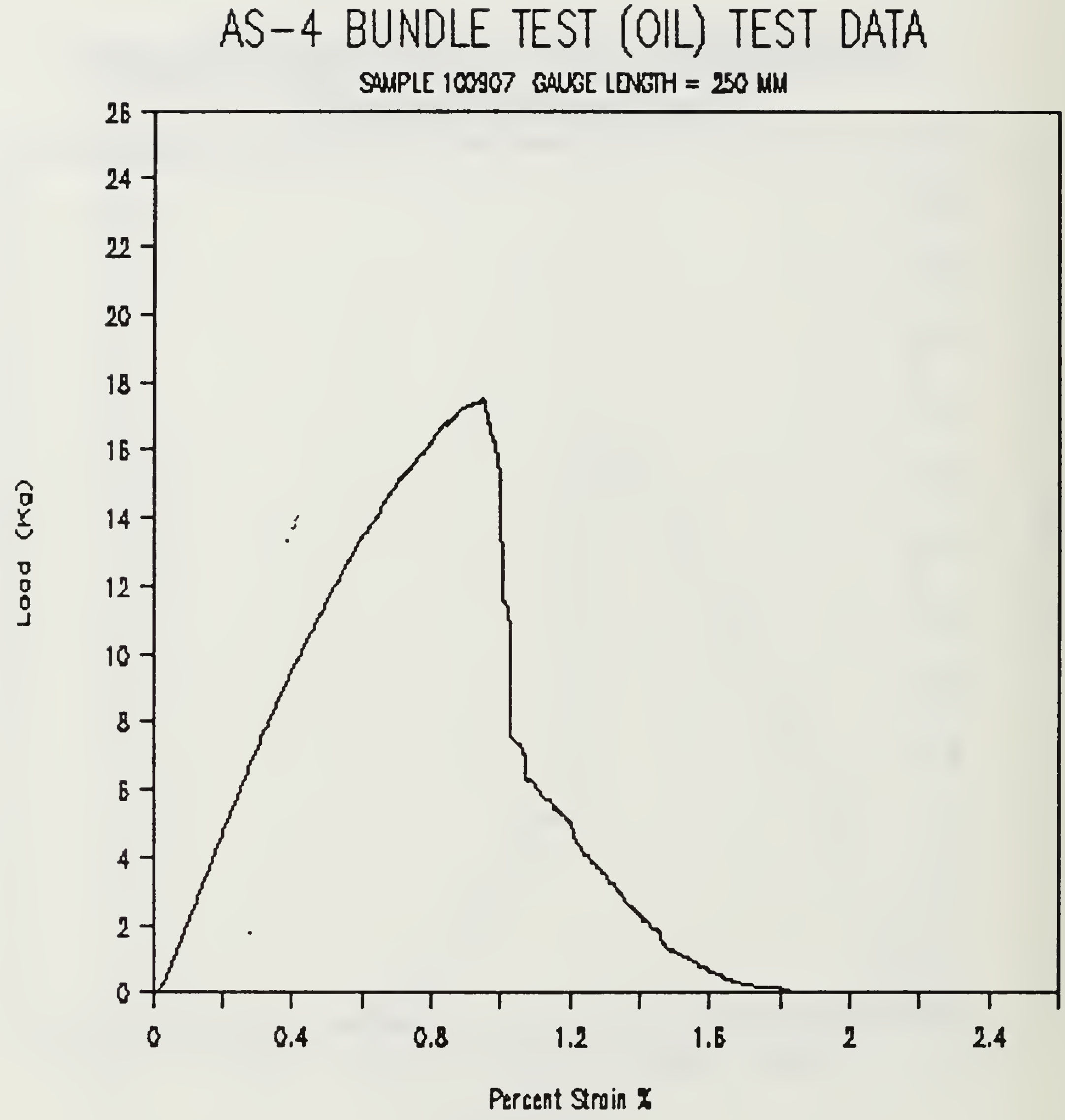


Figure 23

Load vs. Percent Strain Sample 100907 Test Data

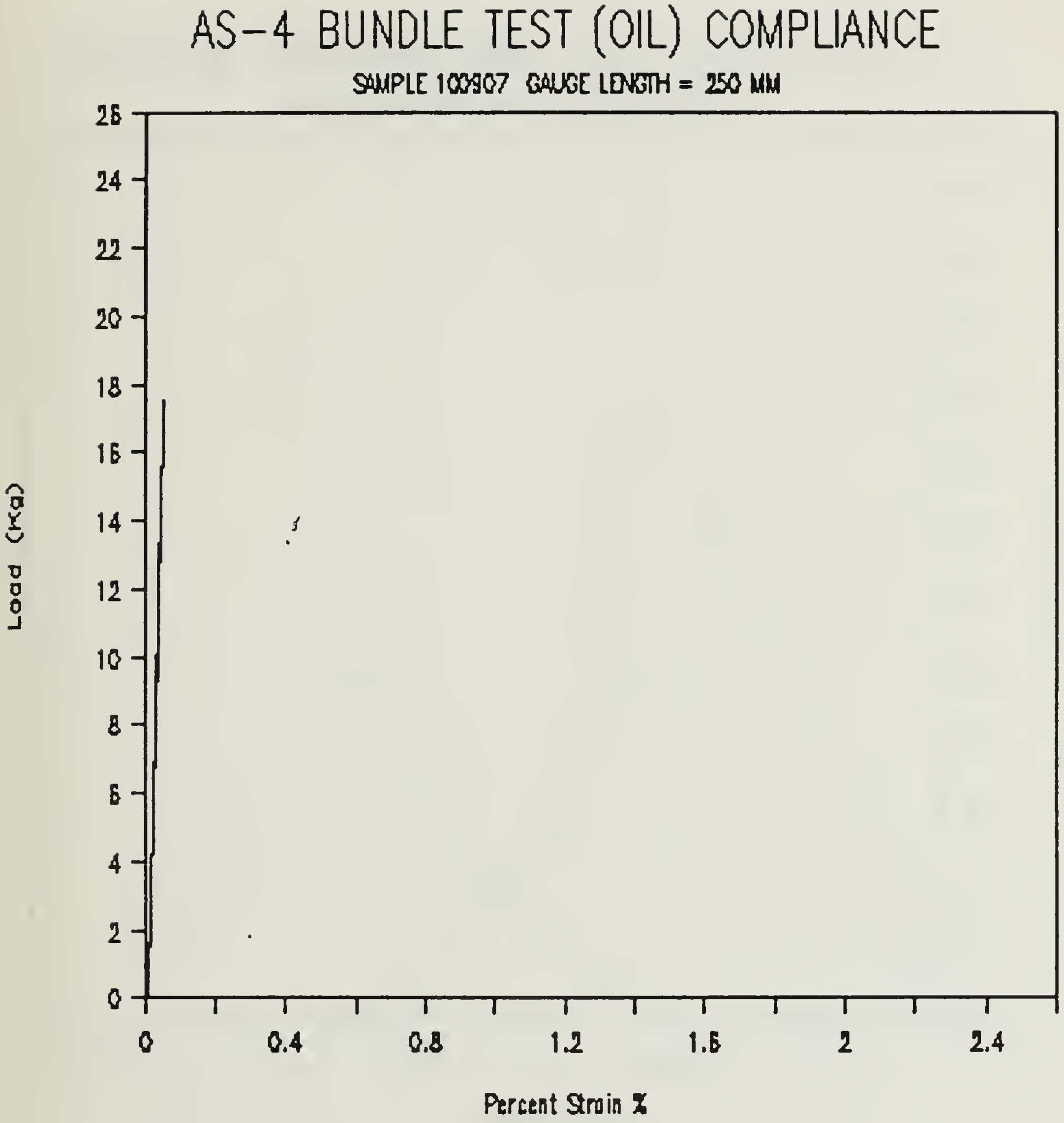


Figure 24

Load vs. Percent Strain Sample 100907 Compliance

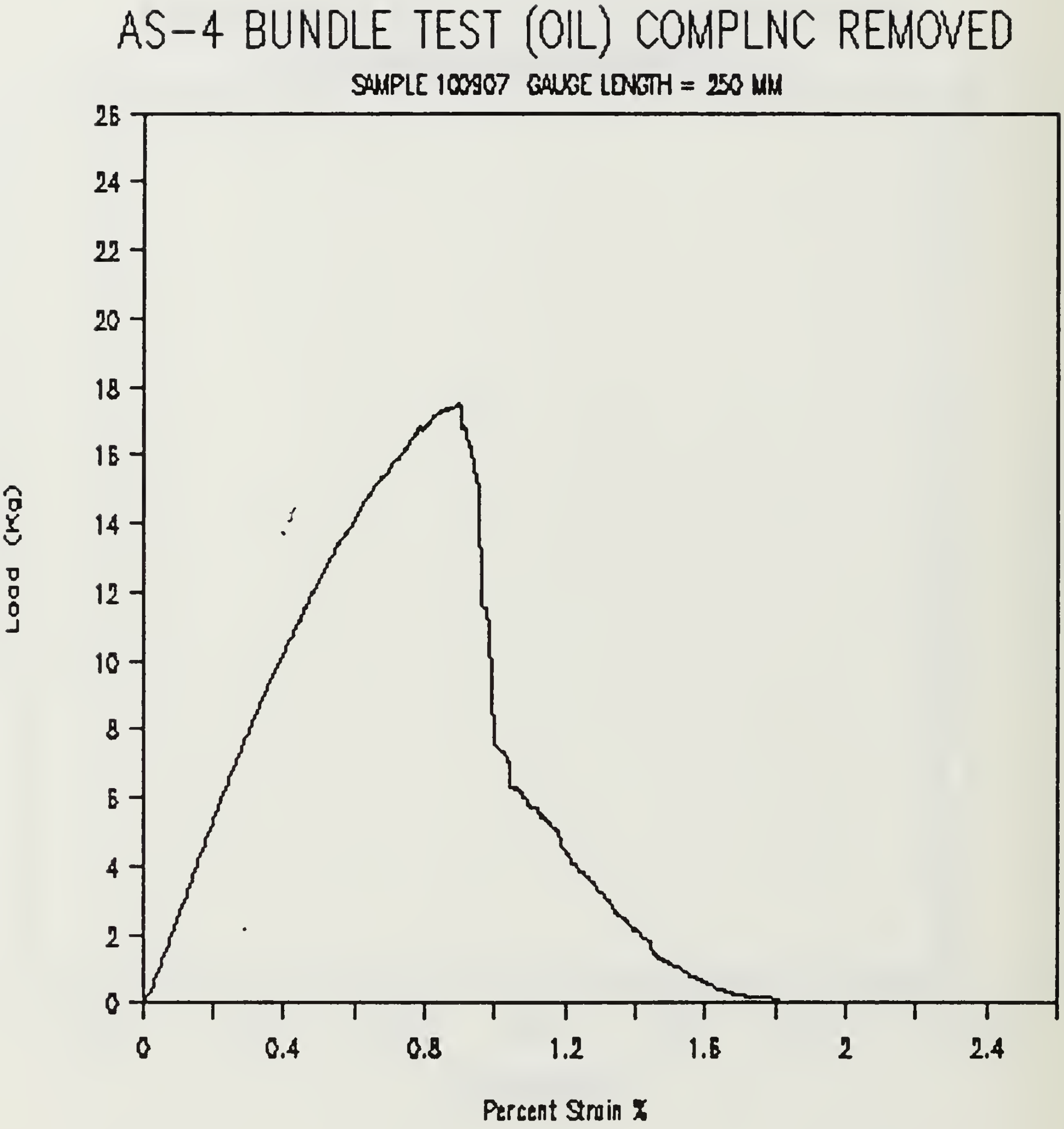


Figure 25

Load vs. Percent Strain Sample 100907 Compliance Removed

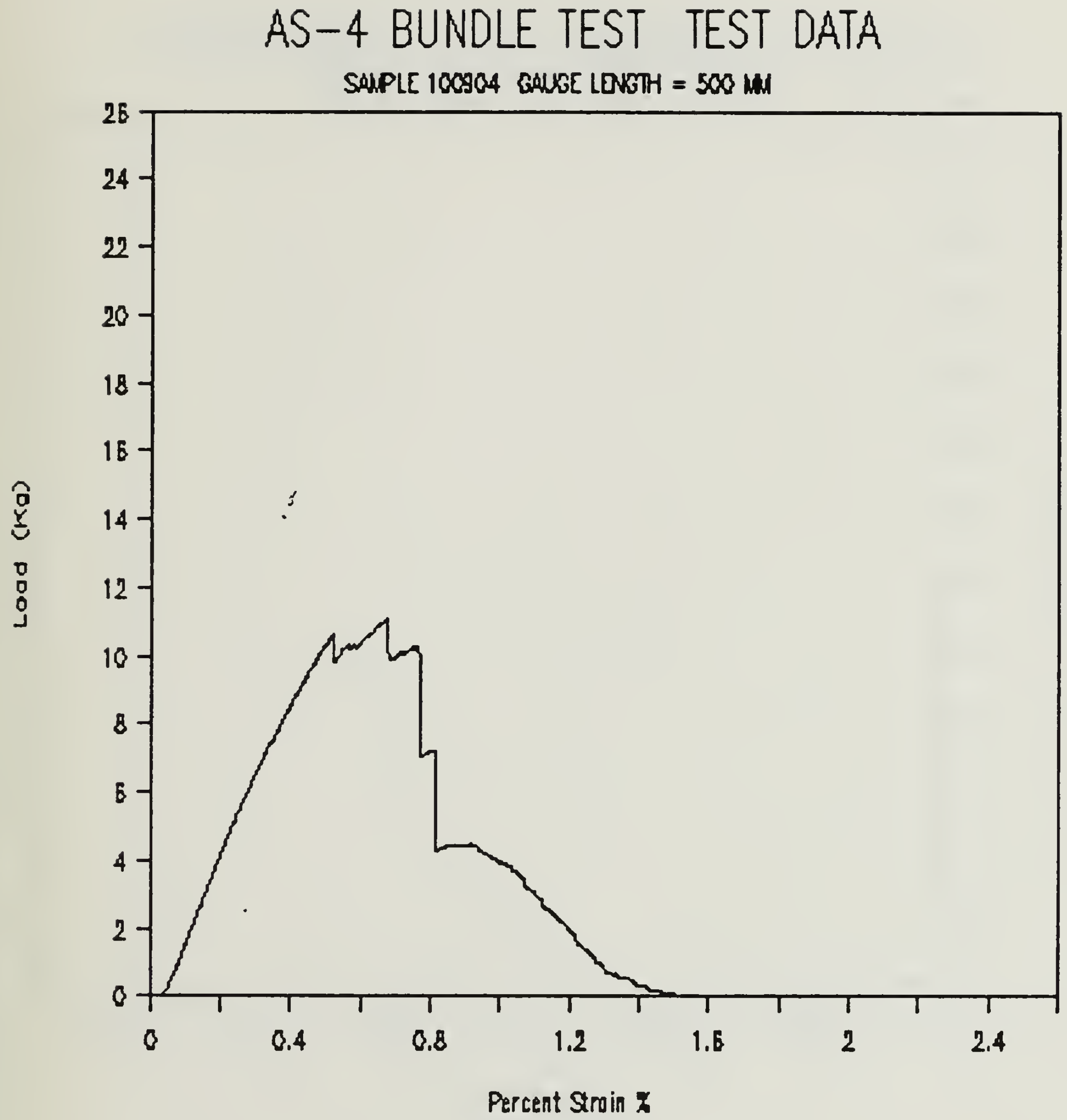


Figure 26

Load vs. Percent Strain Sample 100904 Test Data

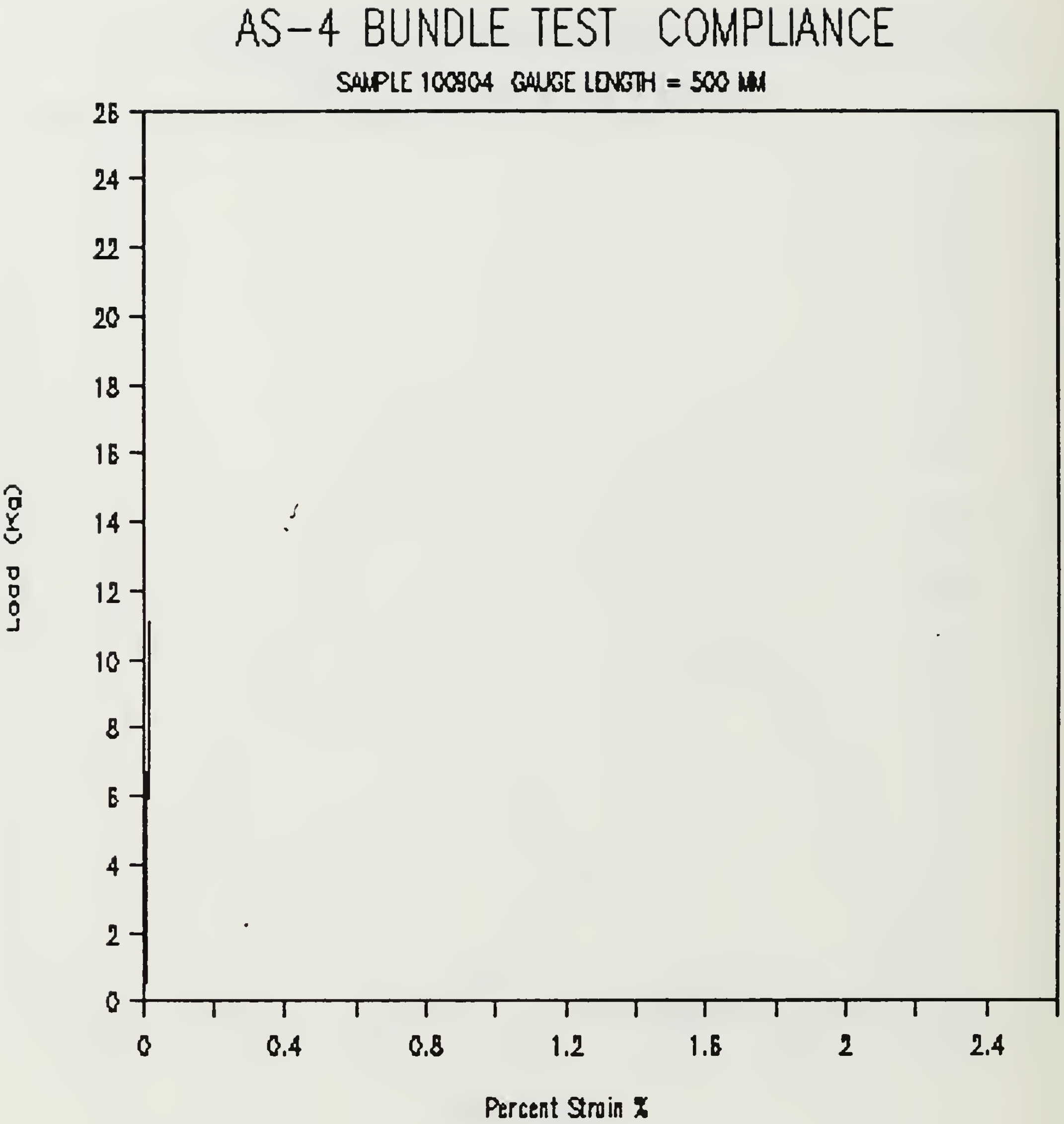


Figure 27

Load vs. Percent Strain Sample 100904 Compliance

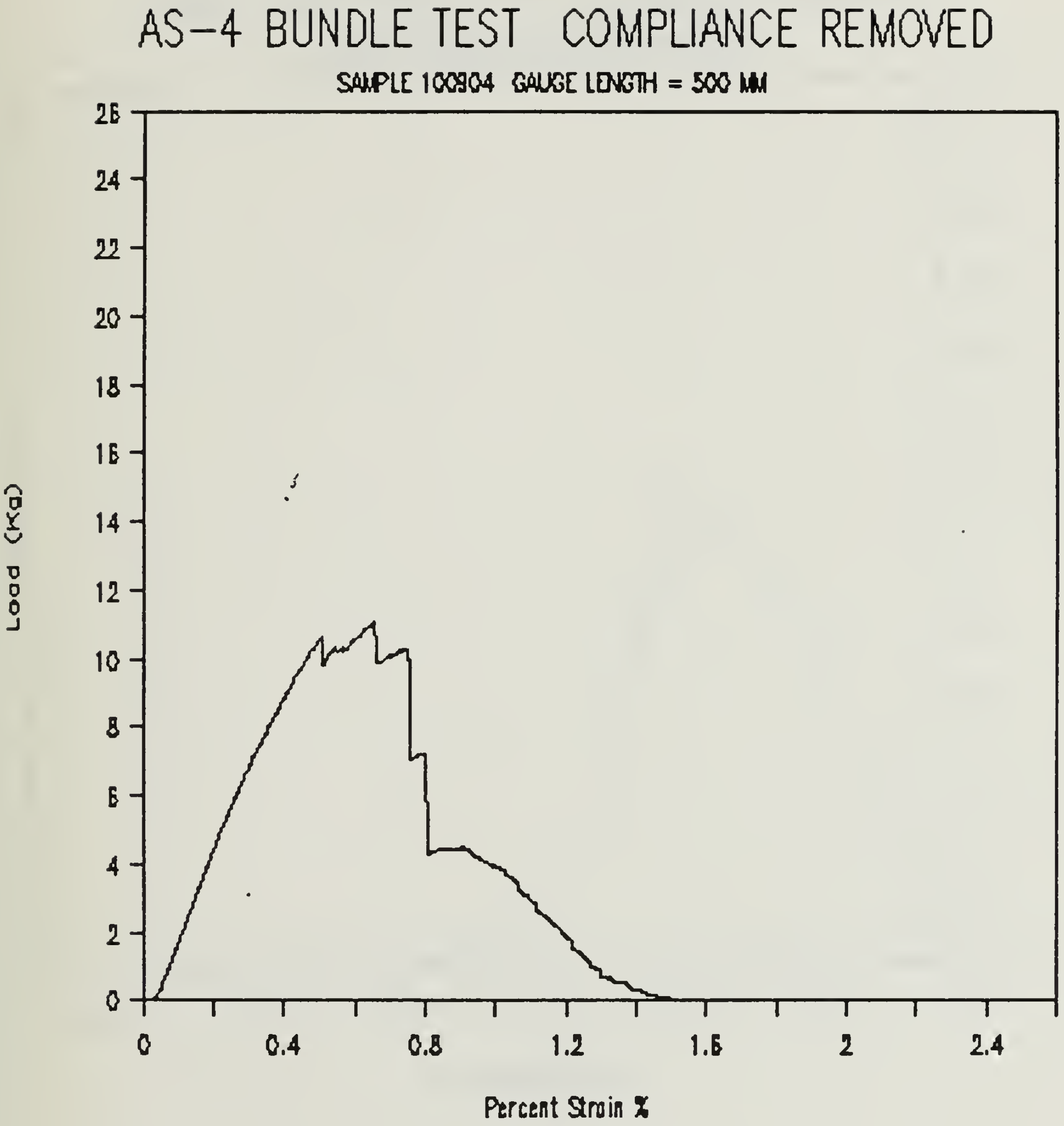


Figure 28

Load vs. Percent Strain Sample 100904 Compliance Removed

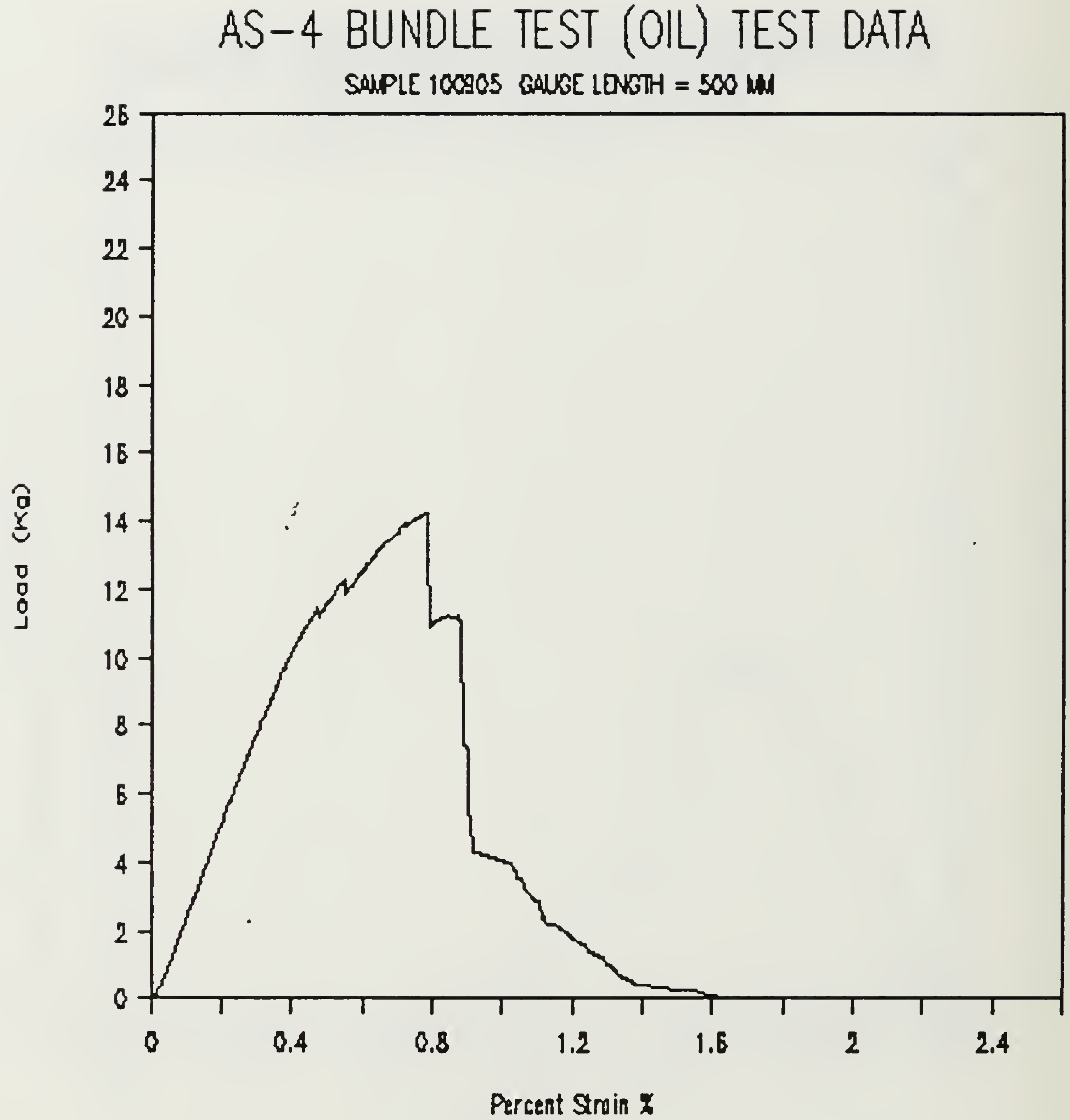


Figure 29

Load vs. Percent Strain Sample 100905 Test Data

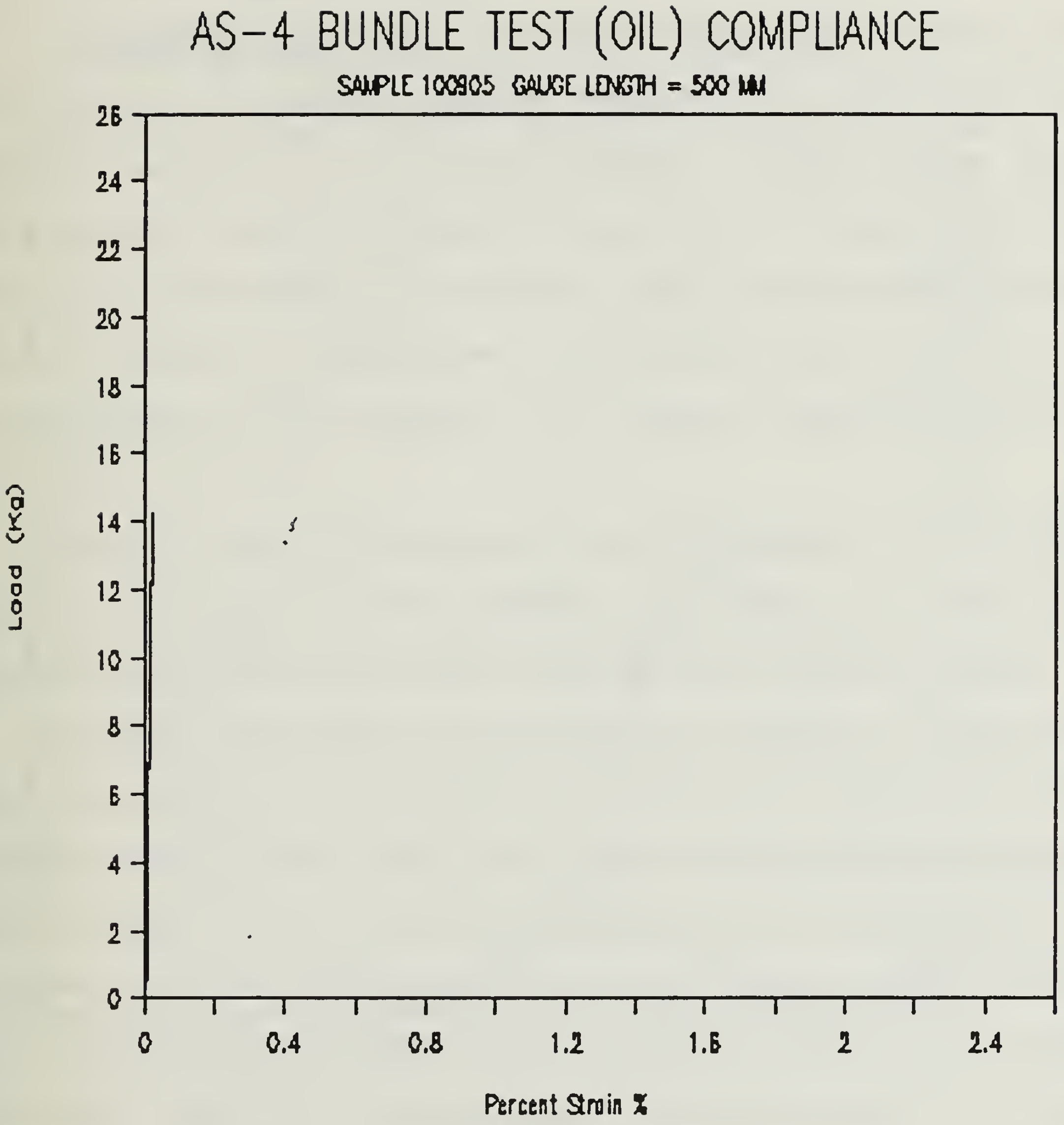


Figure 30

Load vs. Percent Strain Sample 100905 Compliance

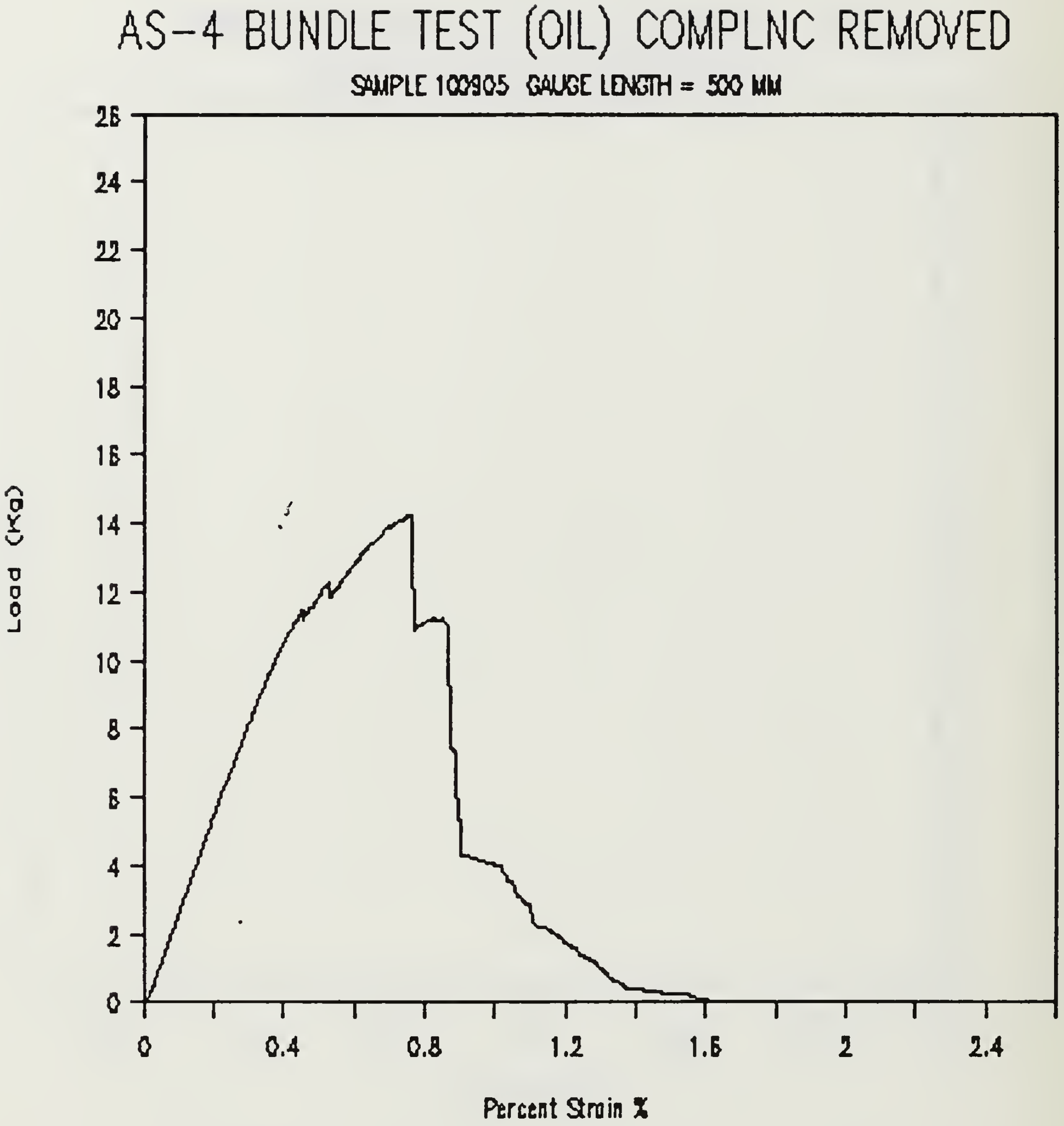


Figure 31

Load vs. Percent Strain Sample 100905 Compliance Removed

V. CONCLUSIONS

A. COMPLIANCE TESTING

The curve-fitting procedure outlined in Appendix C was successful in arriving at a continuous function to describe the load-induced displacement of the load train for the INSTRON testing machine. Figure 32 shows the data points measured during the zero gauge length test. Figure 33 shows the curve fit function using the parameters listed in Table 2. Figure 34 then shows the data points and the curve fit superimposed on one another. The greatest deviation in load is .0017 kg.

Based on the small deviation of the data points to the curve fit function, the curve fit of the compliance is satisfactory to be used to subtract the displacement due to compliance from bundle test data.

The curve fit solution for the machine compliance is satisfactory for loads greater than .1 kg. The curve fit does not do a good job in the region below this load. This is due to the inconsistent zero displacement length. The zero point for displacement is very difficult to achieve for bundle testing. The sensitivity of the load cell is insufficient to consistently identify an actual zero load level on the bundle. The effect of this on the fiber strength distribution parameters is that some elements of the lower tail are distorted.

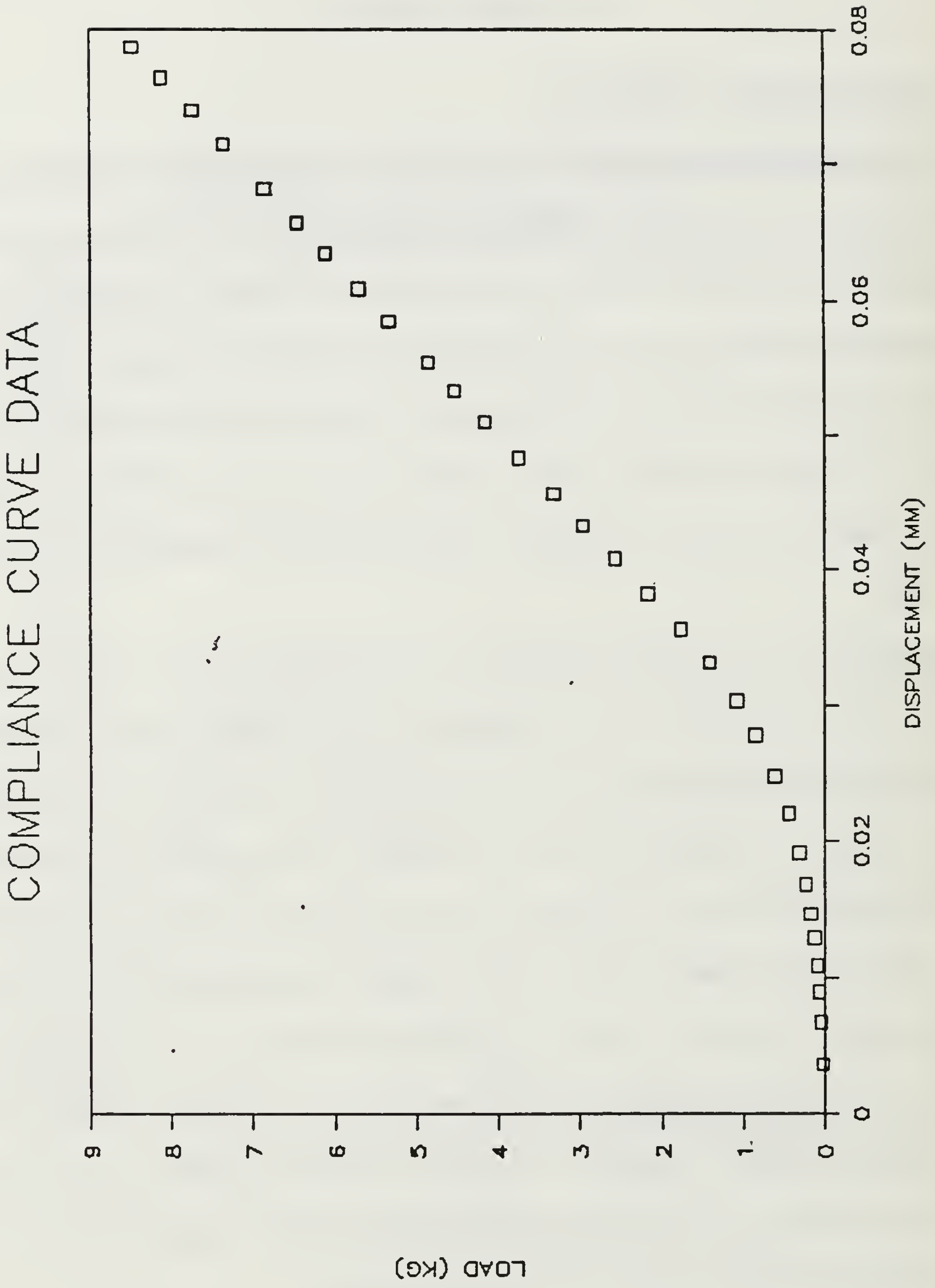


Figure 32

0 Gauge Length INSTRON Compliance Test

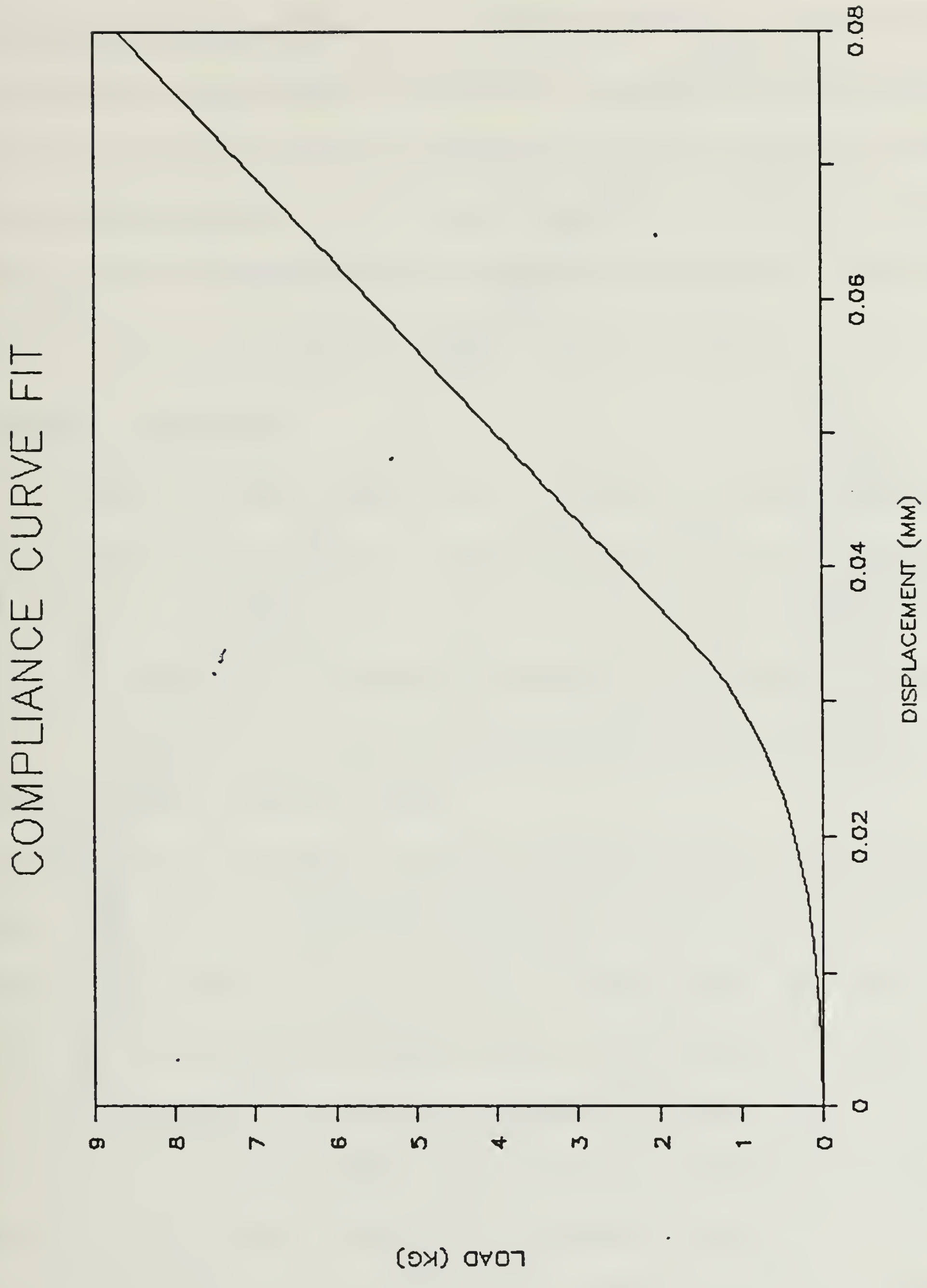


Figure 33

INSTRON Compliance Curve Fit Function

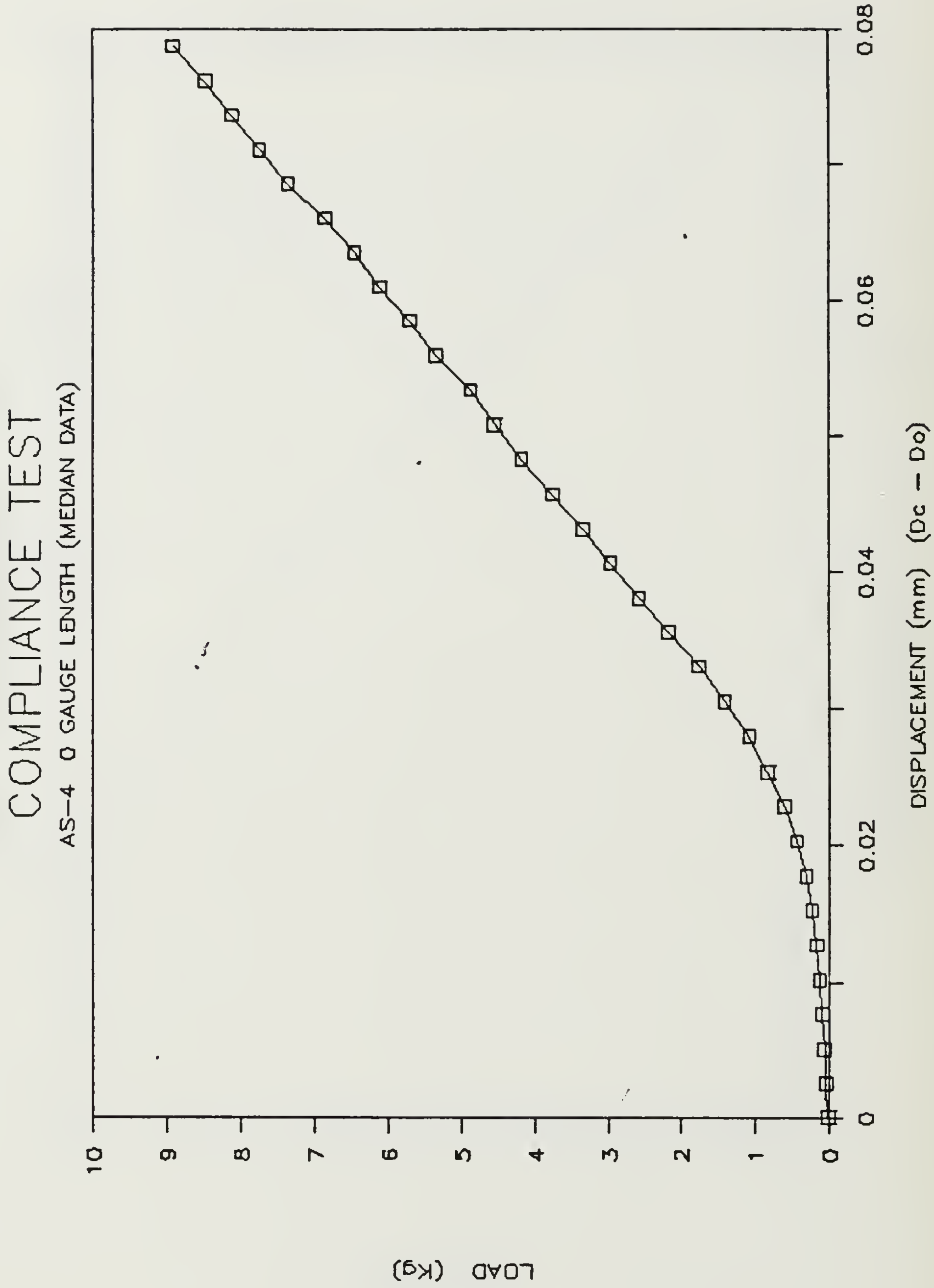


Figure 34

0 Gauge Length INSTRON Compliance Test and Curve Fit

The compliance testing method for the INSTRON has been demonstrated to be feasible and to provide realistic results. Testing should continue to determine whether the compliance is repeatable or whether it is a function of other factors such as temperature, humidity, or age of the machine. Full understanding of compliance is important because of the magnitude of compliance effects on short gauge lengths; it is the short gauge lengths to which stressing is applied.

B. BUNDLE TESTING

The bundle tests demonstrated the difficulty in obtaining test data for short gauge lengths. Table 2 illustrated the fact that no successful 1 cm tests were completed and only one 2.5 cm test was completed. An improved technique of sample preparation to prevent the slipping of the fibers through the tabs is needed. Possibly an adhesive with better wetting qualities could be tried.

The difficulty in testing the small gauge lengths highlights two important effects on prestressing. The first is that the shorter the prestress gauge length, the more difficult the process becomes due to the difficulty in maintaining gauge length. The second important effect is that the prestress effect on fiber parameter improvement will have to be based on a gauge length less than the ineffective length. The optimization process will now include another variable, the minimum possible gauge length due to machine constraints. As the minimum gauge length, increases the effectiveness of the prestress will decrease.

The importance of accurately removing the displacement in the test data for short gauge lengths was demonstrated by the bundle tests. Figures 15, 18, 21, 24, 27, and 30 show that as a function of percent strain, the shorter the gauge length, the greater the percentage of test displacement is due to machine compliance. Figure 15 shows that the percent strain displacement due to compliance for the shortest gauge length (2.5 cm) was greater than .6 percent, or nearly 25 percent of the total test displacement. Figure 27 shows that the percent strain displacement due to compliance for the longest gauge length (50 cm) was less than .02 percent, which is less than 1 percent of the total test displacement.

The inaccuracy incurred in not eliminating the compliance displacement for long samples before reducing the data to determine the fiber strength parameters is minimal. In the case of short samples, however, this is not the case. If the compliance displacement is not removed, the effect on the strength parameters will be the same as if the gauge length was actually longer than what was tested. This results in the fiber parameters being conservative in the prediction of fiber strength. While this is safe, it defeats the purpose of prestressing.

Figures 25 and 31 are the graphs of the oiled bundles. Comparing these graphs to Figures 22 and 28, which are the dry or not oiled samples, the effects of friction can be seen in the shape of the curves after the maximum load has been reached. The dry sample load drops in large vertical jumps. These large jumps correspond to many fibers breaking at once instead of sequentially. Figure 35 shows the simulated test data for a 100 mm sample. The curve is very smooth and does not show the sharp vertical drops the actual test data shows.

The large vertical drops in the actual test data are noticeably reduced, but not eliminated, in the oiled samples. The oil, a soybean derivative, reduces the friction but does not eliminate all of the effects. The effect of friction on the test does appear to dominate the tail end or the final 30 percent of the percent strain. The effect of friction on the fiber strength parameters is difficult to predict. One effect that is clear is that the data for the first 50 percent to 60 percent of the breaks in the long samples do not appear to be affected by friction as the remaining breaks. In addition, Figures 16 and 19 indicate that the effect of friction declines as the gauge length becomes shorter.

The need to eliminate friction between the fibers in a bundle test is important if long-gauge length tests are to be accurately completed. Different oils may be tried as lubricants to improve upon the performance of the soybean oil. If the friction cannot be eliminated, it must be brought down to a minimal level.

The effect of noise in the bundle tests appears to be minimal. Figures 36, 37, and 38 are graphs of simulated bundle tests with noise added to the load data. Figure 4 is a graph of the same simulation with no noise present.

A noise level of 1 gm is equivalent to .002 percent for the 50 kg load cell used by the INSTRON. The difference in the curves from

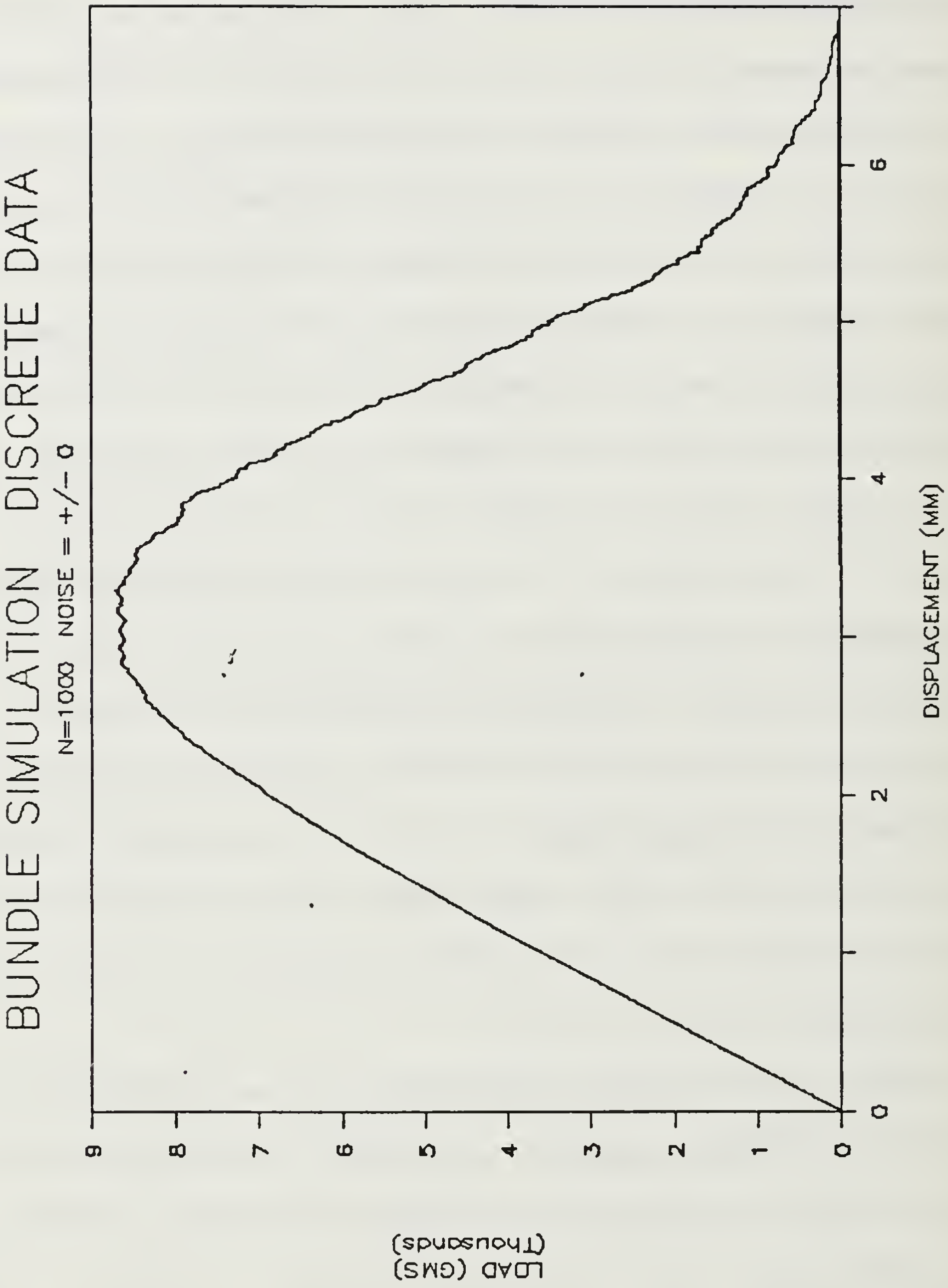


Figure 35

Bundle Test Simulation (Gauge Length—10 cm)

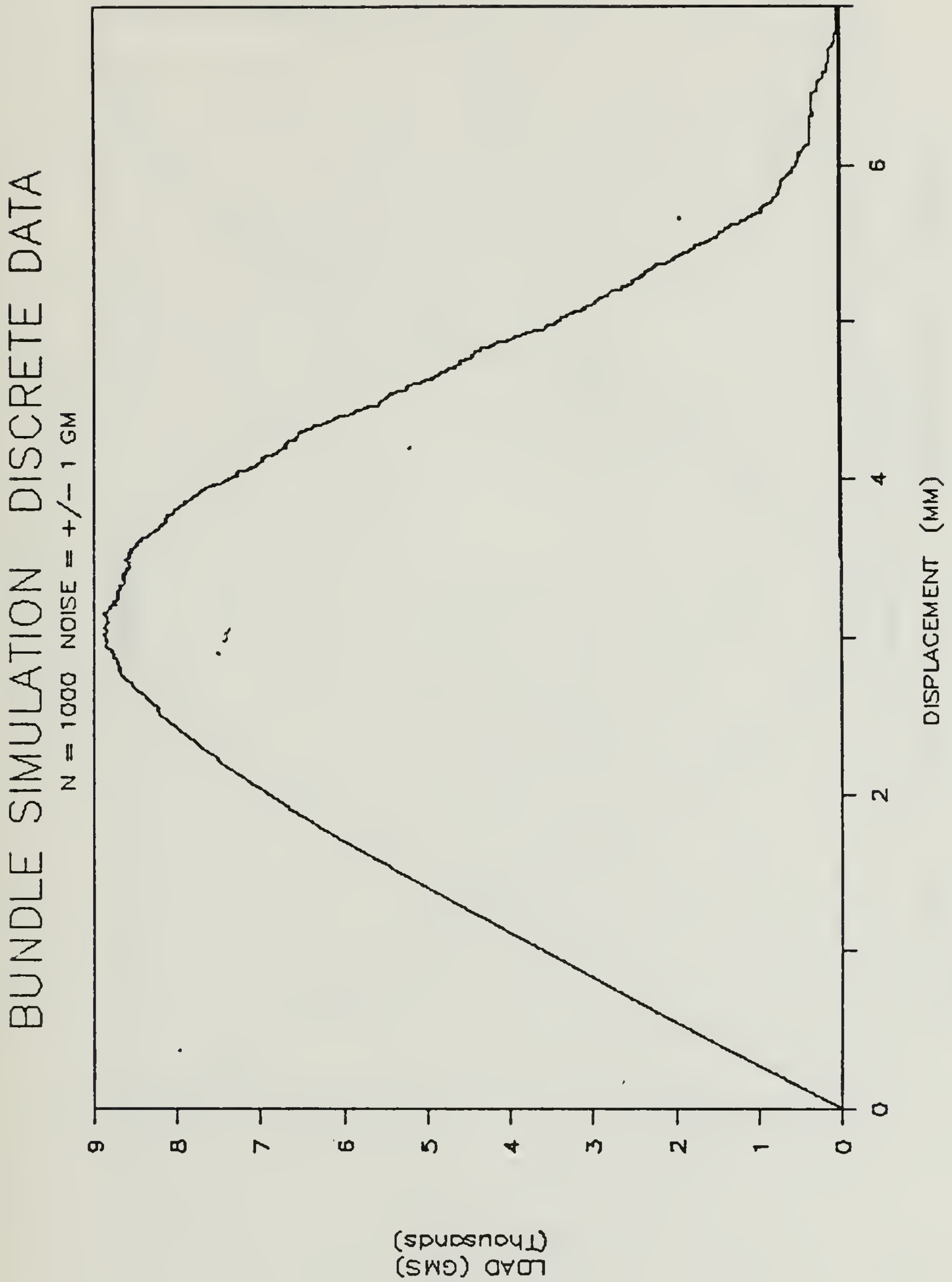


Figure 36

Bundle Test Simulation With ±1 gm Noise

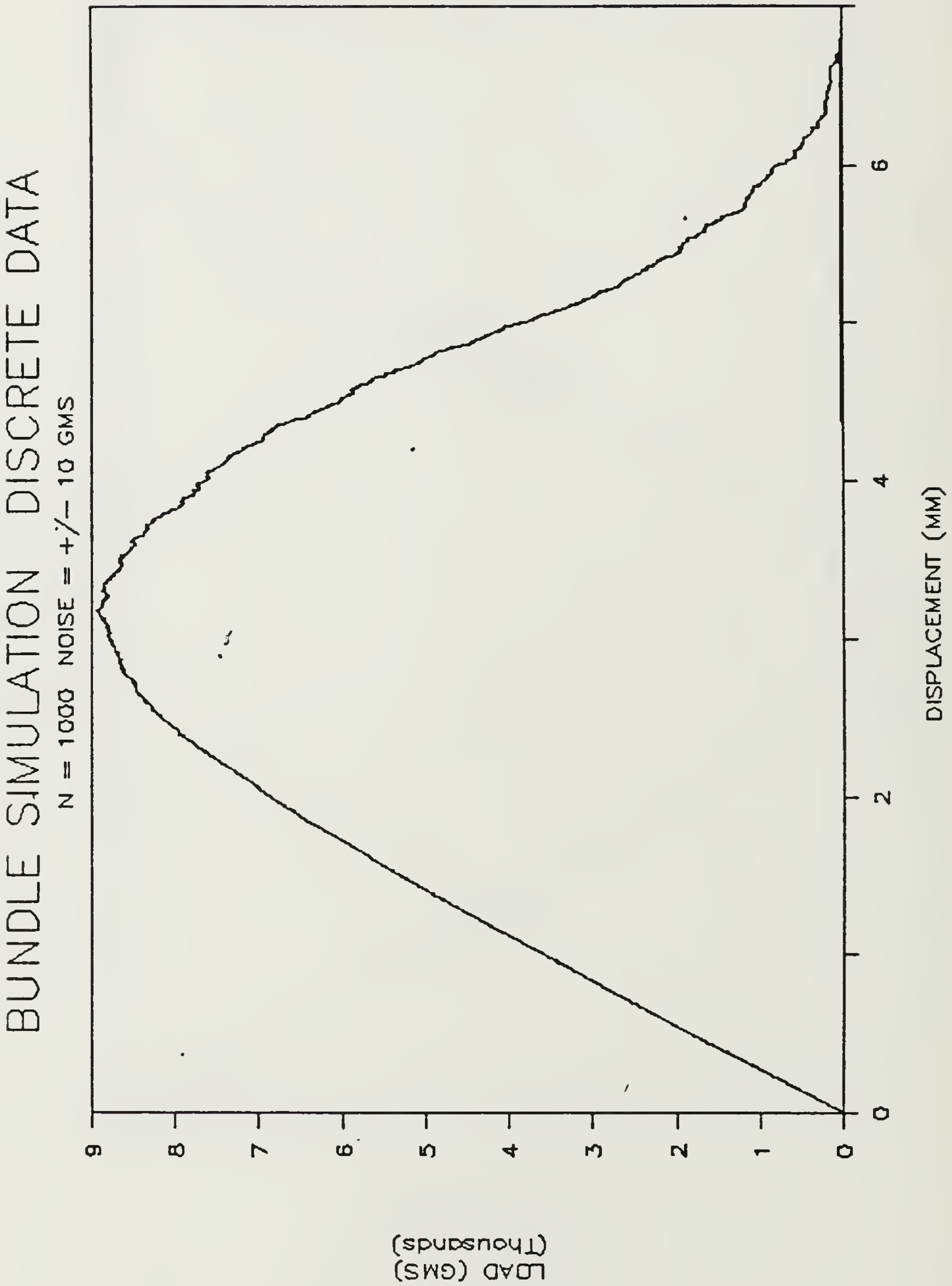


Figure 37

Bundle Test Simulation With ±10 gm Noise

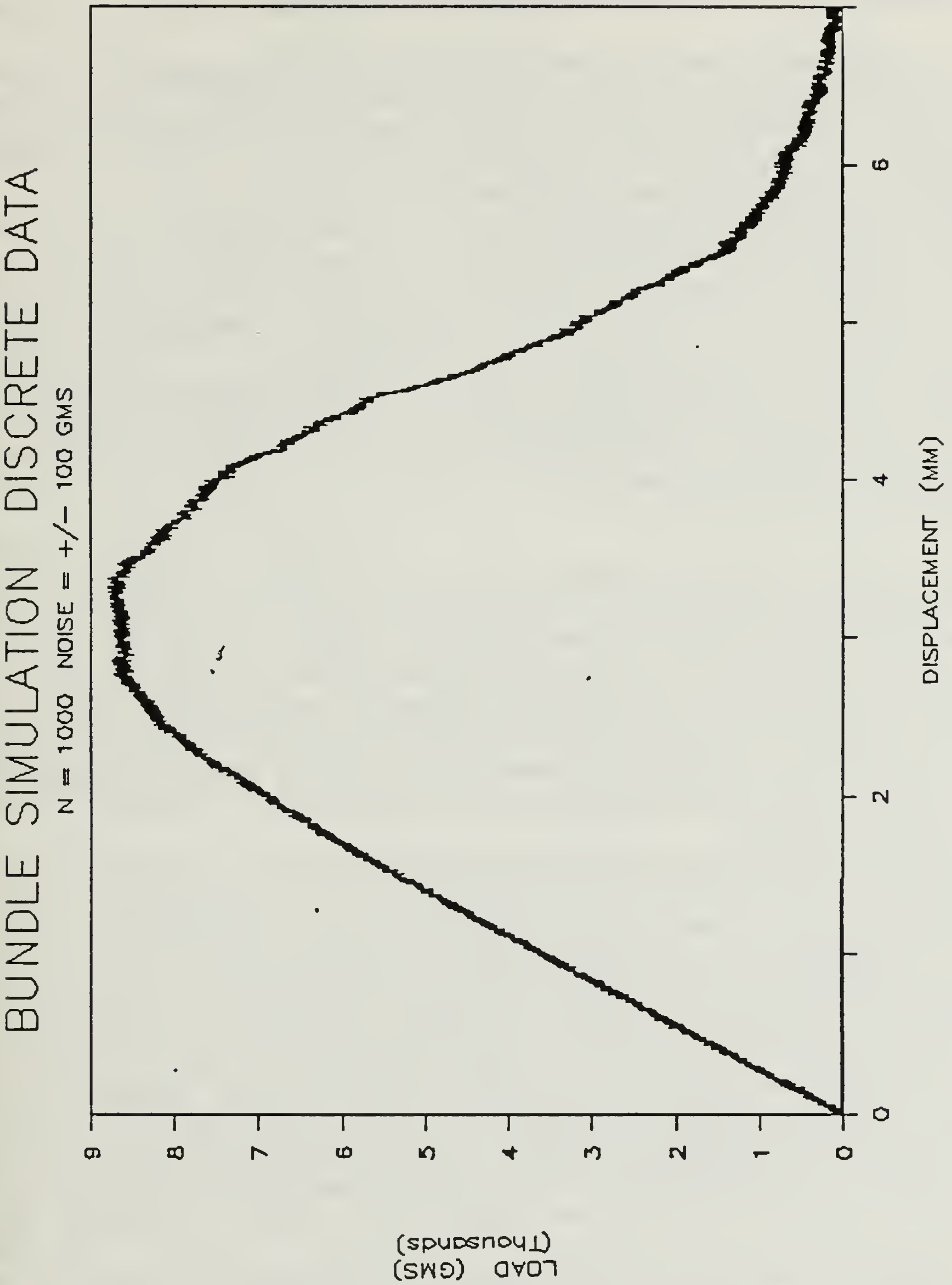


Figure 38

Bundle Test Simulation With ±100 gm Noise

Figure 35 to Figure 36 is barely noticeable. A noise level of 10 gms is equivalent to .02 percent. Figure 37 shows some effects of noise, but they are minimal. A noise level of 100 gms is equivalent to .2 percent. This is an excessive amount of noise and the effects of a noise level this high are clearly shown by Figure 8.

The INSTRON manual specifies the sensitivity, or noise level, of the load cell to be .01 kg. This corresponds to roughly the noise level of Figure 37. An inspection of Figure 37 demonstrates that the effect of this noise level is barely discernable when compared to Figure 35, a simulation with no noise.

This research has demonstrated that the physical process of preloading fibers with a short gauge length is difficult due to the physical limitations of the sample gripping mechanism. More work is required to find an adequate means to grip or restrain the fibers for short gauge lengths.

The removal of the displacement due to compliance in the test results is significant for gauge lengths shorter than 2.5 cm in order to determine accurately the fiber strength distribution parameters. The effect of compliance diminishes with longer gauge lengths. The friction between the fibers in bundle alters the shape of the load vs. displacement curve. Friction has more of an effect on longer samples than on short samples. Friction may be reduced by using oil on the samples, but it does not entirely eliminate the effect. Noise is not a significant factor in altering the data and does not interfere with the strength distribution parameters.

VI. RECOMMENDATIONS

Further study into the magnitude of the machine compliance for the INSTRON 4206 testing machine should be initiated. The effects of temperature, the gripping devices, and repeatability should be investigated. To complete this, a quicker method to determine the curve fit coefficients needs to be developed. A Fortran program that can accurately and quickly solve the curve-fitting routine in Appendix C should be written and validated. A series of compliance tests may then be completed to build a database.

The methods for sample preparation and bundle testing need to become less technician dependent. There are too many areas where mishandling of the samples may introduce errors into the data by damaging the fibers. The reliance on the laboratory technician to build the samples, align the samples, and then set the gauge length all add variability to the data that should be reduced if not eliminated. Hydraulic grips can eliminate the hand- and wrench-tightening procedure required by the current grips. A brace or stand should be designed and built to hold the sample during loading into the INSTRON. This will eliminate much of the handling the sample must now endure.

The prestress effects of preloading the fibers to a load greater than the critical load should be investigated. This is a probability problem whose solution could be integrated into the bundle simulation program. This program could then be used to predict the prestressing performance and then validated with tests performed in the laboratory on gauge lengths that can be successfully tested. This is very important because the poor test results of the short samples indicate that a short preload gauge length (< 1 cm) may be difficult to achieve.

The effects of prestressing with respect to long-term reliability and composite fatigue failure should be investigated. The impact of local load stress cells on long-term reliability needs to be addressed quickly. The urgency of this aspect of prestressing is that due to the nature of fatigue failure, data taking is a very long process.

APPENDIX A

MODEL SELECTION

Composite fiber materials such as graphite, aramid, or boron are characteristically long and thin when compared to the dimensions of the composite. For example, the diameter of a graphite fiber is on the order of 5 microns, while the fiber length can extend to hundreds of feet for a 1 square foot pressure vessel. Under tension, the fibers fail, or break, at positions where flaws or imperfections exist. These flaws cause the fiber to break at loads much below the theoretical strength of the fiber, which is the chemical-bonding strength. The type of the flaw may be scratching, chemical erosion, contamination, or one of many others. The source of the flaw may have come in production, handling, or service use. The spatial location, density, and severity of these flaws determine the strength of each fiber.

A single fiber or filament may be visualized as a chain made up of many links. These links, or segments, each have a unique strength that is limited by the severity of the flaws contained in that segment. The more severe the flaw, the weaker the segment. For a long fiber, one with many segments, the strength of that fiber is only the strength of the most severe flaw, or the weakest link. If the severity of the flaw is known to fall within a certain probability distribution and the location of the flaws are randomly distributed along the fiber, then a "weak link" model can be assumed for predicting the strength of a fiber.

From statistics, the Weibull distribution best fits the "weak link" model. Phoenix and Wu, in Reference 2, describe the Weibull statistical model as it applies to composite fiber strength prediction in detail. In general, the fiber is partitioned into a series of segments (m). The shortest limiting length segment is equal to the ineffective length or effective load transfer length of the fiber. This is on the order of mm for graphite/epoxy. A bundle is then formed by joining several, (n), fibers in parallel. For example, in this project, AS-4 bundles where m equals 1 and n equals 3,000 were tested in the laboratory.

Based on the Weibull weak link model, the failure cumulative density function (CDF) of a fiber can be explicitly written as a function of the two Weibull parameters α and β. The Weibull failure CDF is written as Equation 5.

$$F = 1 - \exp\{-(x/\beta)^{\alpha}\} \tag{5}$$

The two parameters, α and β, correspond to the distribution shape and scale. α adjusts the shape of the distribution by altering the skew and range of values. As shown in Figure 39, a high shape parameter, or α, corresponds to a very narrow distribution; an α equal to 3.5 approximates a normal distribution; and a smaller α corresponds to a very wide distribution with large tails. When α is large, the scale parameter β is approximately the mean. The AS-4 that was tested in this project for a gauge length of 25 cm has an accepted α equal to 4 and a β equal to 16 gm/(mm/mm).

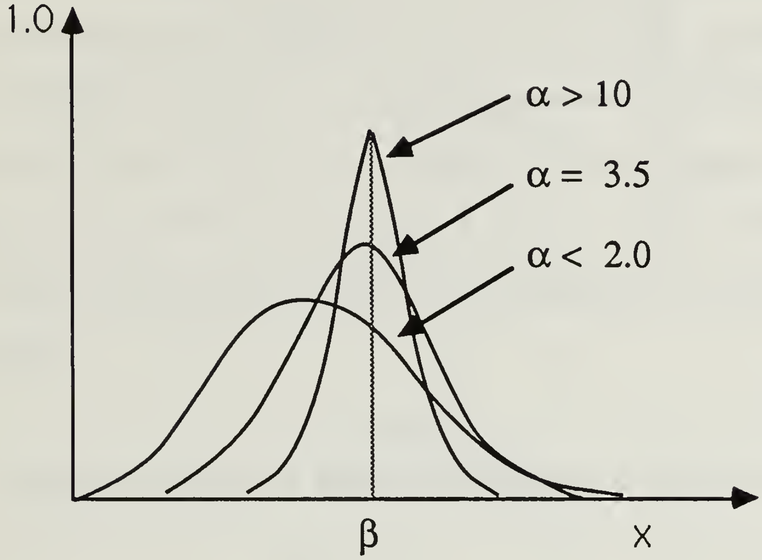


Figure 39

Effect of the Shape Parameter on the Weibull Distribution

The Weibull distribution is not only a physically appropriate model for fiber strength, it has an additional advantage in that its failure cumulative distribution (CDF) can be written as an explicit equation. In addition, the CDF may be linearized with respect to β. This results in Equations 6 and 7. These two equations may then be graphed together to form a graph such as the one shown as Figure 40. This graph of the F*/x* function allows direct graphical correlation of strength to failure probability.

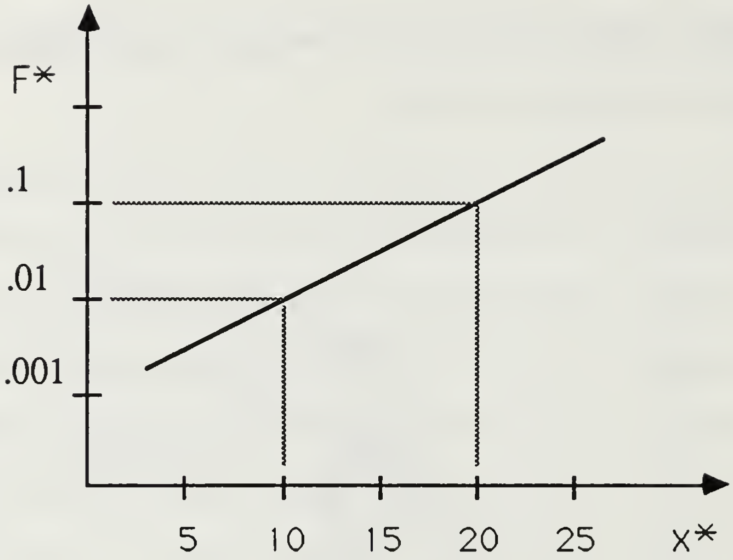


Figure 40

Weibull Linearized Failure Prediction Graph

$$F^* = \ln(-\ln(1 - \exp\{-(P/\beta)^\alpha\})) \tag{6}$$

$$x^* = \ln (P/\beta) \tag{7}$$

where P is the load subjected to the filament.

To predict reliability, which is one minus the failure probability for a fiber, the α and β must be known for that fiber to a sufficient degree of accuracy. Fiber bundle failure tests are performed in the laboratory to arrive at the parameters. A difficulty arrives with the fact that the parameters are a function of the length of a fiber. This corresponds to the fact that a long chain is weaker than a short chain because the longer chain has a higher probability of having a weak segment.

The Weibull model provides a means to normalize the parameters between different lengths of a common fiber if the parameters are known for any one length. This allows for the laboratory results to be applied to fibers of lengths different than the lengths tested. This feature of the Weibull function is commonly called the size effect.

If the strength distribution parameters $\beta 1$ and $\alpha 1$ are known for a fiber of length l_1 and the parameters β_2 and α_2 are desired for the same fiber but of a different length l_2 the following derivation provides the relationship:

$$F_1 = 1 - \exp\{-(x/\beta_1)\alpha_1\} \tag{5}$$

$$R = 1 - F$$

$$(\text{Reliability} = 1 - \text{Failure}) \tag{8}$$

$$R_1 = \exp\{-(x/\beta_1)^{\alpha_1}\} \tag{9}$$

$$m = l_1/l_2 \tag{10}$$

$$R_T = \Pi\, R_1\, R_2 \,\ldots\ldots\ldots = (R_1)^m$$

$$R_T = [\exp\{-(x/\beta_1)^{\alpha_1}\}]^m \tag{11}$$

$$R_2 = \exp\{-m(x/\beta_1)^{\alpha_1}\} \tag{12}$$

$$R_2 = \exp\{-(x/\beta_2)^{\alpha_2}\} \tag{9}$$

Equating Equations 9 and 12 then:

$$\exp\{-m(x/\beta_1)^{\alpha_1}\} = \exp\{-(x/\beta_2)^{\alpha_2}\}$$

$$\{-m(x/\beta_1)^{\alpha_1}\} = \{-(x/\beta_2)^{\alpha_2}\}$$

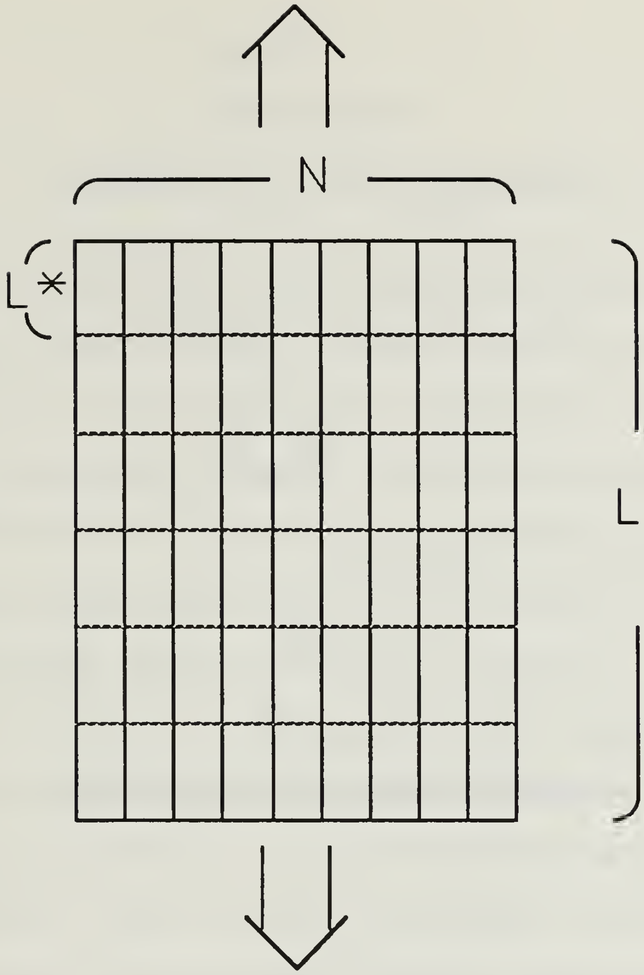
$$(x/(m)^{-1/\alpha_1}\,\beta_1)^{\alpha_1} = (x/\beta_2\,)^{\alpha_2} \qquad (13)$$

Solving Equation 13 results in Equations 14 and 15.

$$\alpha_2 = \alpha_1 \qquad (14)$$

$$\beta_2 = \beta_1(m)^{-1/\alpha_1} \qquad (15)$$

An implication of the size effect relations, Equations 14 and 15, is that a long composite made up of many segments may be reduced to a composite of one segment. This simplification provides for easier mathematical modeling of the composite as a large composite model shown in Figure 41 with many segments may be reduced to the much smaller model shown in Figure 42. This greatly reduces the amount of computational effort required to model composite strength or bundle strength as the model matrix has been reduced from a (m X n) to a (1 X n).



$M = L/L^* = 6$

$N = 10$

Figure 41

Composite Model Without Size Effect

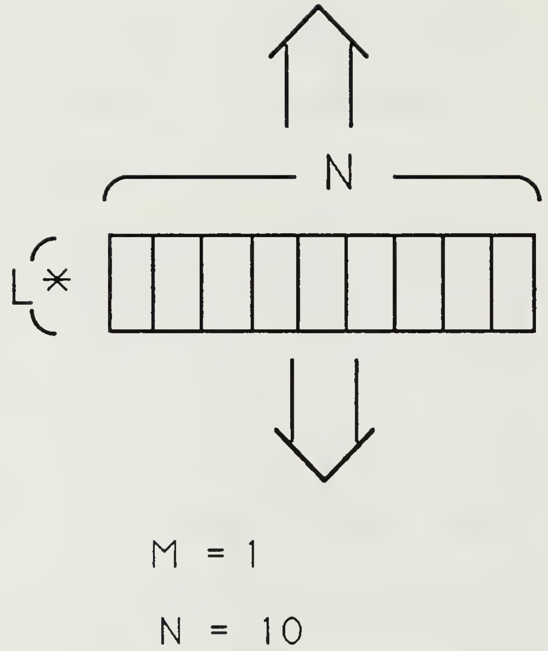


Figure 42

Composite Model With Size Effect

APPENDIX B

BUNDLE FAILURE SIMULATION

The purpose of the bundle failure simulation was twofold. The first was to allow the user to readily produce simulated bundle test data with variable fiber strength distribution parameters. The resulting data could then be graphically presented into load versus displacement or load verses percent strain representations. These graphs were utilized to gain understanding and insight into the effect of fiber strength parameters and gauge length on fiber failure process.

The second purpose of the bundle failure simulation was to provide a means of verification for data interpretation and reduction software being developed for use in conjunction with the INSTRON Testing machine used in the Composites Laboratory, Naval Postgraduate School. The simulation could be used to ensure that the software returned the parameters from the simulated test data that were used as inputs to the bundle simulation. For this project, the compliance removal procedures and software described in Appendices C and D were validated with this program. Lt. Joseph Schmidt, in a separate project, used this program to validate software that reduced bundle test data into the fiber strength probability distribution parameters.

The bundle failure simulation program "T2" takes fiber strength distribution parameters α and β for the length of the bundle, the number of filaments, the length of the bundle, the fiber modulus, and testing machine settings of cross-head speed and sampling rate, and then produces two sets of load vs. displacement data. The first set is the loaded and displacement determined for each individual filament break. This is referred to as the analog data. The second set, which simulates fiber testing machine data, is the continuous load and incremental displacement data, which is referred to as discrete data. The program also has the added feature of inputting a noise range. The maximum number of filaments is 1,000.

The program solves for the strength of each filament based on the Weibull distribution and the size effect. An explanation of the Weibull function and of the size effect is detailed in Appendix A.

A. ANALOG DATA SIMULATION

The analog data was determined by using a random number generator to to generate a random strength of each fiber, determine the displacement of each break, and then compute the load of the bundle at each break.

Equation 16 was used to determine the strength of each fiber.

$$P_f = \ln(-\ln(1 - \exp\{-(x/\beta)^{\alpha}\})) \tag{16}$$

where P_f = failure load of the the fiber

x = random number $0 < x < 1$

Equation 17, which is a manipulation of Hooke's law, is used to determine the displacement of each fiber at the failure load.

$$d_f = P_f * l/E \qquad (17)$$

where d_f = Displacement of the Fiber

l = Length of the Fiber (Gauge Length)

E = Strain Modulus

The displacement at each break was stored in an array and then sorted in ascending order. The load of the bundle at each break was then determined by using Equation 18. This is also a manipulation of Hooke's Law. At each break, because the simulation is for a controlled displacement, the load in the bundle drops by a factor of 1/n. This data point is solved for by Equation 19.

$$(P_b)_i = ((d_f)_i * E * (n-i+1))/l \qquad (18)$$

$$(P_b)_{i+} = ((d_f)_i * E * (n-i))/l \qquad (19)$$

where $i = 1,2,3, \ldots n$ (Number of Breaks)

B. DISCRETE DATA SIMULATION

The discrete data was found by utilizing the analog data. The analog data was transformed into a continuous function by connecting the data points. The displacement between data points is found by Equation 20.

$$\mathrm{Deld} = \mathrm{CHS}/\mathrm{SR} \qquad (20)$$

where CHS = Cross-head Speed (mm/min)

SR = Sampling Rate (pts/sec)

The discrete data displacement is in increments of Deld while the discrete data load is the intercept of the analog continuous data for that appropriate displacement. Equation 21 is used to compute the discrete displacement points. Discrete data points are solved for until the load reaches zero.

$$d = \text{Deld} * I \qquad I = 0,1,2, \ldots \text{Load} = 0 \tag{21}$$

C. NOISE SIMULATION

The user has the option of simulating the effects of noise in the load transducer of a bundle test. If desired, the noise is added to the discrete load data by Equation 22.

$$P_{noise} = P - ((P_h - P_l)/2) + X * (P_h - P_l) \tag{22}$$

where P = Original Load

P_h = High Noise Range

P_l = Low Noise Range

D. PROGRAM LISTING

The program was written in Microsoft Fortran 4.01. It is designed to be operated from any IBM/Compatible computer with two floppy drives or hard disk and one floppy drive. The executable program is run from the A: drive or the hard disk and the data is written to the B: drive. To execute the program type: T5 <enter>.

SUBROUTINE LISTING:

INIT	Initializes arrays to zero
INPUT	Prompts user to input required value
RAND	Random number generator (user must input seed)
SLOAD	Solves for the breaking stress of each filament
SORT	Sorts the filaments by breaking stress and then solves for breaking displacement
ANLDAT	Creates the analog load and displacement file
DISDAT	Solves for the continuous and creates the discrete load and displacement file
NOISE	Allows user to input random noise to a specified threshold into the discrete load data
OUTPUT	Writes the analog and discrete data to floppy disks

VARIABLE LISTING:

DATA(0:1000,7)	Workspace array
ADATA(0:2000,2)	Analog data output file; Displacement, Load, listed sequentially by first break to last
DDATA(0:2000,2)	Discrete data output file; Displacement, Load, listed as a function of sampling time
ALPHA	Weibull shape parameter for the given length
BETA	Weibull scale parameter for the given length
E	Modulus of fiber
L	Length of the Fiber
N	Number of filaments in the bundle (max. = 1,000)
CHS	Simulated testing machine cross-head speed

SR	Simulated machine sampling rate
DELD	Distance between data points for discrete data
POINTS	Number of discrete data points
SEED	Random number generator seed for strength computations
SEED1	Random number generator seed for discrete data load during break generator
SEED2	Random number generator seed for noise generator
BREAKS	Counter that is used to find slope of analog data for up to n-1 breaks
LIMIT	Maximum strength of fiber $_i$ used in solving for the maximum displacement for n-1 breaks
PH	Upper noise range
PL	Lower noise range

OUTPUT FILES

ADATA	Analog data; displacement, load
DDATA	Discrete data; index, displacement, load

```
       PROGRAM T2
************************************************************************
*   PROGRAM T2 WILL SIMULATE A BUNDLE TEST FOR N FIBERS IN PARALEL     *
*   FOR GIVEN FIBER STRENGTH PARAMETERS AND LENGTH OF THE BUNDLE.      *
*   THE PROGRAM WILL OUTPUT ANALOG DATA THAT IS A LISTING OF THE       *
*   DISPLACEMENT AND LOAD OF EACH FIBER BREAK.   THE PROGRAM WILL      *
*   OUTPUT DISCRETE DATA THAT SIMULATES MACHINE TESTING DATA FOR THE   *
*   BUNDLE.  THE OUTPUT IS BY INDEX, DISPLACEMENT AND LOAD.  THE       *
*   NUMBER OF DATA POINTS IS A FUNCTION OF THE SIMULATED CROSSHEAD     *
*   SPEED AND THE SAMPLING RATE.                                       *
*                                                                      *
*   THE OUTPUT IS WRITTEN TO DRIVE B:  ADATA.  AND DDATA.              *
*                                                                      *
************************************************************************

* DECLARATION STATEMENTS
      REAL DATA(0;1000,7), DDATA(0;5000,2),ALPHA,BETA,L,CHS,PH,PL,
     1E,DELD,SR,ADATA(0;2000,2)
      INTEGER N,I,J,K,POINTS,Q
    1 CONTINUE

* PRINT BANNER AND START PROGRAM
      PRINT*,'COMPOSITE BUNDLE TEST SIMULATION PROGRAM'
      CALL INIT(DATA,DDATA,ADATA)
      CALL INPUT(ALPHA,BETA,L,CHS,E,N,SR)
      CALL RAND(DATA,N)
      CALL SLOAD(DATA,N,ALPHA,BETA)
      CALL SORT(DATA,N,E,L)
      CALL ANLDAT(DATA,N)
      CALL DISDAT(DDATA,DATA,N,E,L,CHS,SR,POINTS)
      CALL NOISE(DDATA,POINTS)
      CALL OUTPUT(DATA,DDATA,N,E,L,ALPHA,BETA,POINTS,ADATA)

* ALLOW USER TO RERUN PROGRAM
      PRINT*
      PRINT*,'RUN COMPLETE, DO YOU WISH TO RUN ANOTHER SET OF DATA'
      PRINT*,' IF YES TYPE 1, ELSE TYPE 0 TO EXIT PROGRAM'
      READ*, Q
      IF(Q .EQ. 1) GOTO 1

* PRINT BANNER AND END PROGRAM
      PRINT*
      PRINT*,' END OF RUN,    HAVE A NICE DAY'
      END
************************************************************************
*   SUBROUTINE INIT                                                    *
*                                                                      *
*   SUBROUTINE INIT INITIALIZES THE ARRAYS TO ZERO                     *
************************************************************************

* DECLARATION STATEMENTS
      SUBROUTINE INIT(DATA,DDATA,ADATA)
      REAL DATA(0;1000,7),DDATA(0;5000,2),ADATA(0;2000,2)
      INTEGER I,J

* PRINT BANNER AND START SUBROUTINE
```

```
      PRINT*
      PRINT*,'***** RUNNING INITIALIZATION SUBROUTINE *****'
      PRINT*
      DO 10 I = 0,1000
      DO 9 J = 1,7
      DATA(I,J) = 0.
    9 CONTINUE
   10 CONTINUE
      DO 20 I = 0, 5000
      DO 19 J = 1,2
      DDATA(I,J) = 0.
   19 CONTINUE
   20 CONTINUE
      DO 30 I = 0, 2000
      DO 29 J = 1,2
      ADATA(I,J) = 0
   29 CONTINUE
   30 CONTINUE
      END
************************************************************************
*   SUBROUTINE INPUT                                                   *
*                                                                      *
*   SUBROUTINE INPUT PROMPTS THE USER TO INPUT THE REQUIRED            *
*   DATA TO PERFORM THE SIMULATION.  INPUTS ARE:                       *
*                                                                      *
*   ALPHA, BETA, N, L, E -  FIBER PARAMETERS                           *
*   CHS,  SR             -  TESTING MACHINE PARAMETERS                 *
*                                                                      *
************************************************************************

* DECLARATION STATEMENTS
      SUBROUTINE INPUT(ALPHA,BETA,L,CHS,E,N,SR)
      REAL ALPHA,BETA,CHS,L,SR,E
      INTEGER N

* PRINT BANNER AND START SUBROUTINE
      PRINT*
      PRINT*,'***** RUNNING INPUT SUBROUTINE *****'
      PRINT*
      PRINT*,'INPUT ALPHA AND BETA FIBER PARAMETERS'
      READ*, ALPHA, BETA
      PRINT*,'INPUT NUMBER OF FILAMENTS IN BUNDLE (MAX = 1000)'
      READ*, N
      PRINT*,'INPUT MEAN BUNDLE LENGTH (CM)'
      READ*, L
      L = L*10
      PRINT*,'INPUT LOAD MODULUS OF FIBER (GM/MM/MM)'
      READ*, E
      PRINT*,'INPUT SIMULATION CROSSHEAD SPEED (MM/MIN)'
      READ*, CHS
      PRINT*,'INPUT SIMULATION SAMPLING RATE (PTS/SEC)'
      READ*, SR
      PRINT*
      PRINT*,'INPUT COMPLETE'
      PRINT*
      END
************************************************************************
*   SUBROUTINE RAND                                                    *
*                                                                      *
*   SUBROUTINE RAND GENERATES A RANDOM NUMBER FROM 0 TO 1 FOR EACH     *
*   FILAMENT IN THE BUNDLE.  THE RANDOM NUMBER GENERATOR IS STARTED    *
*   FROM THE INITIAL INPUT SEED.  THE FUNCTION RAND IS USED TO         *
*   ACTUALLY FIND THE RANDOM NUMBER.                                   *
*                                                                      *
************************************************************************
      SUBROUTINE RAND(DATA,N)

* DECLARATION STATEMENTS
      REAL DATA(0;1000,7),RNG
      INTEGER N, SEED, I

* PRINT BANNER AND START SUBROUTINE
      PRINT*
      PRINT*,'***** RUNNING RANDOM NUMBER GENERATOR SUBROUTINE *****'
      PRINT*
      PRINT*
      PRINT*,'INPUT ANY ODD INTEGER (STRENGTH RNG SEED)'
      READ*, SEED
      PRINT*
      DO 100 I = 1, N
      DATA(I,1) = I
      DATA(I,3) = RNG(SEED)
  100 CONTINUE
      END
************************************************************************
*   SUBROUTINE SLOAD                                                   *
*                                                                      *
*   SUBROUTINE SLOAD WILL GENERATE A BREAKING STRENGTH FOR EACH        *
*   FILAMENT AND FROM THE MODULUS FIND THE CORESPONDING DISPLACEMENT.  *
*                                                                      *
************************************************************************
      SUBROUTINE SLOAD(DATA, N,ALPHA,BETA)

* DECLARATION STATEMENTS
      REAL DATA(0;1000,7),ALPHA,BETA
      INTEGER N

* PRINT BANNER AND START SUBROUTINE
      PRINT*
      PRINT*,'***** RUNNING SIMULATION LOAD SUBROUTINE *****'
      PRINT*
      DO 100 I = 1, N

* BREAKING STRENGTH EQUATION BASED ON WEIBULL ALPHA AND BETA PARAMETERS
      DATA(I,4) = EXP((LOG(-LOG(1-DATA(I,3)))+ALPHA*LOG(BETA))/ALPHA)
  100 CONTINUE
      END
************************************************************************
*   SUBROUTINE SORT                                                    *
*                                                                      *
*   SUBROUTINE SORT USES A BUBBLE SORT METHOD TO SORT THE FILAMENTS    *
*   FROM LOWEST TO HIGHEST BY BREAKING POINT DISPLACEMENT.            *
*                                                                      *
************************************************************************
      SUBROUTINE SORT(DATA,N,E,L)

* DECLARATION STATEMENTS
      REAL DATA(0;1000,7),T4,T5,E,L
      INTEGER N,PAIRS,T1
      LOGICAL DONE

* PRINT BANNER AND START SUBROUTINE
      PRINT*
      PRINT*,'***** RUNNING SORT SUBROUTINE *****'
      PRINT*
      PAIRS= N-1
      DONE = .FALSE.
   20 IF(.NOT. DONE) THEN
      DONE = .TRUE.
      DO 30 I = 1,PAIRS
      IF(DATA(I,4) .GT. DATA(I+1,4)) THEN
      T4 = DATA(I,4)
      T1 = DATA(I,1)
      DATA(I,4) = DATA(I+1,4)
      DATA(I,1) = DATA(I+1,1)
      DATA(I+1,4) = T4
      DATA(I+1,1) = T1
      DONE = .FALSE.
      ENDIF
   30 CONTINUE
      PAIRS = PAIRS - 1
      GOTO 20
      ENDIF
      PRINT*
      PRINT*,'*** SORT COMPLETE, NEW INDEX BEING ADDED TO DATA***'
      PRINT*
      DO 40 I = 1, N
      DATA(I,2) = I
   40 CONTINUE
      PRINT*
      PRINT*,'*** SOLVING FOR DISPLACEMENT BASED ON BREAK LOADS ***'
      PRINT*
      DO 50 I = 1,N
      DATA(I,5) = (DATA(I,4)*L)/(E)
   50 CONTINUE
      END
************************************************************************
*  SUBROUTINE ANLDAT                                                   *
*                                                                      *
*  SUBROUTINE ANLDAT WRITES THE DISPLACEMENT AND LOAD OF EACH BREAK    *
*  INTO ARRAY ADATA                                                    *
*                                                                      *
************************************************************************
      SUBROUTINE ANLDAT(DATA,N)

* DECLARATION STATEMENTS
      REAL DATA(0;1000,7)
      INTEGER N

* PRINT BANNER AND START SUBROUTINE
      PRINT*
      PRINT*,'***** RUNNING ANALOG DATA FILE SUBROUTINE *****'
      PRINT*
      DO 100 I = 1, N
      DATA(I,6) = (N-I+1)*DATA(I,4)
      DATA(I,7) = (N-I)*DATA(I,4)
  100 CONTINUE
      END
************************************************************************
*  SUBROUTINE DISDAT                                                   *
*                                                                      *
*  SUBROUTINE DISDAT CREATES LOAD AND DISPLACEMENT BASED ON THE        *
*  DATA BUT THE DISPLACEMENT IS CONTROLLED BY THE MACHINE CROSSHEA     *
*  SPEED AND THE DATA SAMPLING RATE.  A RANDOM NUMBER GENERATOR IS     *
*  USED TO SOLVE FOR THE LOAD IF THE DISPLACEMENT OCCURS AT A BREAK   *
*  POINT.                                                              *
*                                                                      *
************************************************************************
      SUBROUTINE DISDAT(DDATA,DATA,N,E,L,CHS,SR,POINTS)

* DECLARATION STATEMENTS
      REAL DDATA(0;5000,2),DATA(0;1000,7),E,CHS,SR,DELD,DISP,LIMIT,
     1 RANGE,RNG,L
      INTEGER SEED1,BREAKS,POINTS,N

* PRINT BANNER AND START SUBROUTINE
      PRINT*
      PRINT*,'***** RUNNING DISCRETE DATA SUBROUTINE *****'
      PRINT*
      PRINT*,'INPUT ANY ODD INTEGER (RNG SEED)'
      READ*,SEED1
      DELD = CHS/(SR*60)
      BREAKS = 0

*  SET LIMIT EQUAL TO DISPLACEMET OF FIRST BREAK
      LIMIT = DATA(1,5)
      DO 100 I = 1,5000
      DISP = DELD*I
  150 CONTINUE
      IF(DISP .LT. LIMIT) THEN
      DDATA(I,1) = DISP
      DDATA(I,2) = ((N - BREAKS)*E*DISP)/L
      GOTO 199
      ENDIF
      IF(DISP .EQ. LIMIT) THEN
      RANGE = (((N - BREAKS)*E*DISP)-((N-BREAKS-1)*E*DISP))/L
      DDATA(I,2) = (RNG(SEED1)*RANGE)+(((N-BREAKS-1)*E*DISP)/L)
      DDATA(I,1) = DISP
      GOTO 199
      ENDIF
      BREAKS = BREAKS + 1
      IF(BREAKS .EQ. N) GOTO 200
```

```
* INCREMENT TO NEXT BREAK DISPLACEMENT
      LIMIT = DATA(BREAKS+1,5)
      GOTO 150
  199 CONTINUE
  100 CONTINUE
  200 CONTINUE

* POINTS = NUMBER OF DISCRETE DATA POINTS
      POINTS = I
      END
************************************************************************
*  SUBROUTINE NOISE                                                    *
*                                                                      *
*  SUBROUTINE NOISE ALLOWS THE USER TO SIMULATE MACHINE NOISE IN THE   *
*  DISCRETE LOAD DATA.  THE USER INPUTS THE RANGE OF THE NOISE AND     *
*  A RANDOM NUMBER GENERATOR IS USED TO FIND A NOISE FOR EACH DATA     *
*  LOAD IN BETWEEN THE GIVEN RANGE.                                    *
*                                                                      *
************************************************************************
      SUBROUTINE NOISE(DDATA, POINTS)

* DECLARATION STATEMENTS
      REAL DDATA(0;5000,2),PH,PL,RNG
      INTEGER I,Q,SEED2,POINTS

* PRINT BANNER AND START SUBROUTINE
      PRINT*
      PRINT*,'***** RUNNING NOISE SUBROUTINE *****'
      PRINT*
      PRINT*,'DO YOU WANT TO ENTER NOISE INTO DISCRETE DATA'
      PRINT*,'IF YES TYPE 1, IF NO TYPE 0'
      READ*,Q
      IF(Q .NE. 1)GOTO 200
      PRINT*,'INPUT ANY ODD INTEGER (RNG SEED)'
      PRINT*
      READ*,SEED2
      PRINT*,'INPUT HIGH NOISE RANGE AND LOW NOISE RANGE  (GMS)'
      READ*, PH, PL
      DO 100 I = 0, POINTS
      DDATA(I,2) = (DDATA(I,2) -((PH-PL)/2)) + RNG(SEED2)*(PH-PL)
  100 CONTINUE
  200 CONTINUE
      END
************************************************************************
*  SUBROUTINE OUTPUT                                                   *
*                                                                      *
*  SUBROUTINE OUTPUT WRITES THE ANALOG DATA AND THE DISCRETE DATA      *
*  ONTO DRIVE-B OUTPUT FILES                                           *
*                                                                      *
************************************************************************
      SUBROUTINE OUTPUT(DATA,DDATA,N,E,L,ALPHA,BETA,POINTS,ADATA)
      REAL DATA(0;1000,7),DDATA(0;5000,2),E,ALPHA,BETA,L,
     1ADATA(0;2000,2)
      INTEGER N,POINTS,Q1,Q2,I,II
      PRINT*,'***** RUNNING OUTPUT SUBROUTINE *****'
      PRINT*
      PRINT*,'DO YOU DESIRE A LISTING OF THE ANALOG DATA'
      PRINT*,'IF YES TYPE 1, IF NO TYPE ZERO'
      READ*,Q1
      PRINT*,'DO YOU DESIRE A LISTING OF THE DISCRETE DATA'
      PRINT*,'IF YES TYPE 1, IF NO TYPE ZERO'
      READ*,Q2
      IF(Q1 .EQ. 1) THEN

* WRITE THE ANALOG DATA
      PRINT*
      OPEN(15, FILE='ADATA')
      WRITE(15, 960)
  960 FORMAT(  /  '   DISP    LOAD')
      DO 105 I = 1,N
      II = (2*I)-1
      ADATA(II,1) = DATA(I,5)
      ADATA(II+1,1) = DATA(I,5)
      ADATA(II,2) = DATA(I,6)
      ADATA(II+1,2) = DATA(I,7)
  105 CONTINUE
      DO 106 I = 0,2*N
      WRITE(15,961) ADATA(I,1), ADATA(I,2)
  106 CONTINUE
  961 FORMAT(  F10.6,2X,F10.4)
      CLOSE(15)
      PRINT*
      PRINT*,' ANALOG DATA IS IN FILE "ADATA FILE"'
      PRINT*
      ENDIF
      IF(Q2 .EQ. 1) THEN

* WRITE THE DISCRETE DATA
      OPEN(15, FILE='DDATA')
      WRITE(15,951)
  951 FORMAT(/ 'POINT       DISP        LOAD')
      DO 110 I = 0,POINTS
      WRITE(15,901)I, DDATA(I,1),DDATA(I,2)
  110 CONTINUE
      PRINT*,' DISCRETE DATA IS IN FILE "DDATA FILE"'
      PRINT*
      CLOSE(15)
      ENDIF
  901 FORMAT(  I5,2X,F10.6, 4X,F10.4)
      END
**********************************************************************
*    FUNCTION RNG(SEED)  RANDOM NUMBER GENERATOR                     *
**********************************************************************
      FUNCTION RNG(K)
      INTEGER K,M,CONST1
      REAL RNG, CONST2
      PARAMETER(CONST1=2147483647, CONST2=.4656613E-9)
      SAVE
      DATA M /0/
      IF(M .EQ. 0) M = K
      M = M*65539
      IF(M .LT. 0) M = (M+1) + CONST1
      RNG = M * CONST2
      END
```

APPENDIX C

COMPLIANCE REMOVAL

The objective of the analysis of fiber bundle testing data is to determine the fiber strength distribution parameters. To this end, the actual fiber displacement data must be obtained from the total test displacement data. A significant portion of the test displacement data is due to machine compliance. This appendix describes a method to determine this displacement and subtract it from the test displacement data consisting of the load train displacement and the sample displacement.

A. ISOLATION OF COMPLIANCE

Fiber bundle testing is accomplished with the use of the Instron Universal Testing Instrument Model 4206 (INSTRON) machine. The fiber test records displacement and the load measured by the INSTRON load cell. The test is controlled by software that operates the machine on a controlled cross-head speed and takes data at a user-selected sampling rate. The machine is schematically illustrated in Figure 43.

A typical bundle test load vs displacement graph is shown in Figure 44. The curve may be partitioned into three regions. Region I is the concave non-linear region. This is concavity is due to the compliance on the load train and the variation in gauge length (slack) amount of each filament.

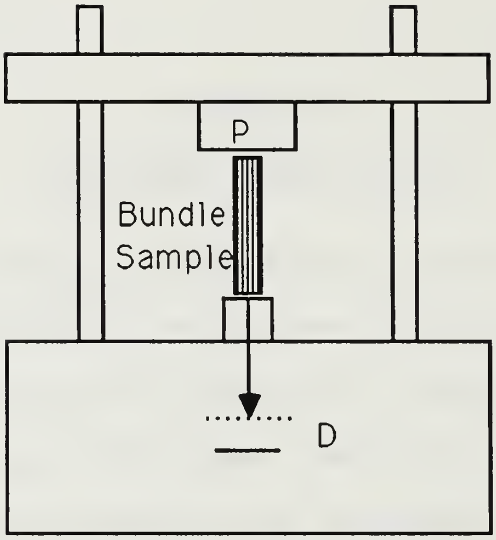


Figure 43

INSTRON Testing Machine

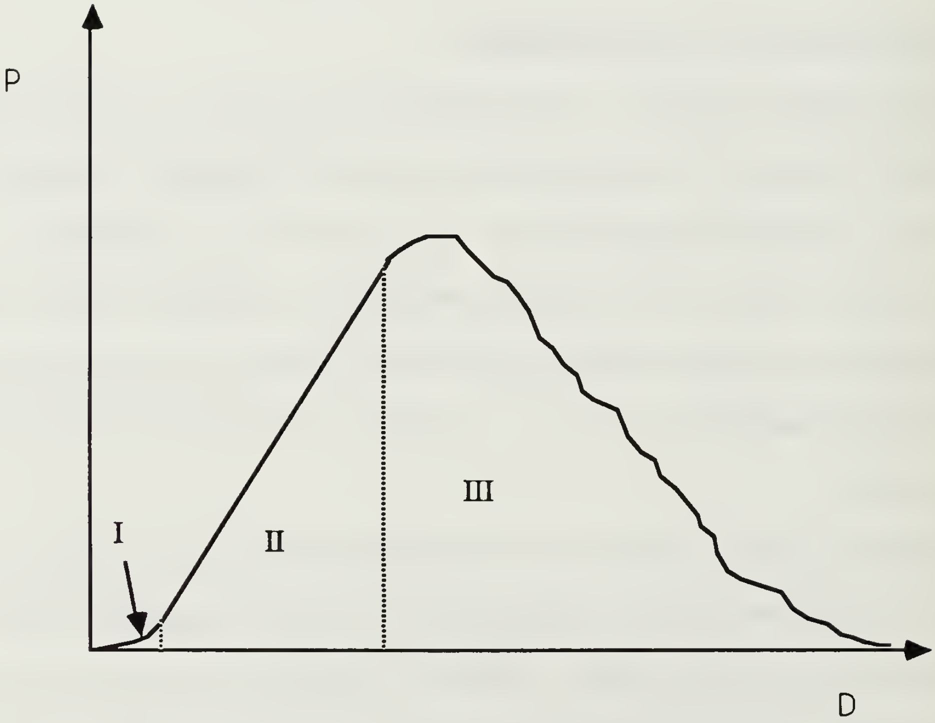


Figure 44

Typical Bundle Test Load vs. Displacement Graph

This is due to each filament of the bundle not having exactly the same gauge length; the curve becomes progressively steeper as each filament starts to carry the load. Region II is the linear region. Here all of the filaments are carrying the load equally. The bundle displacement is a linear function of displacement due to Hooke's Linear Stress-Strain law shown in Equation 23.

$$P = nE\delta$$

$$\delta = P/nE \tag{23}$$

where P = load

n = number of filaments

E = filament modulus

δ = displacement

Region III is the failure region where the load fluctuates as each fiber breaks.

The load data that the INSTRON records is derived from an electrical signal from the load cell. This load is the load taken by the fibers, but also includes the load taken up by the testing machine load train. This load causes deformations in the load train consisting of the gears of the machine, the grips, grip base, and all other structural components. These components of the load train combined to form machine compliance. The INSTRON shown in Figure 43 may now be modeled as shown in Figure 45. The INSTRON is equivalent to two springs in series, the machine compliance and the fibers.

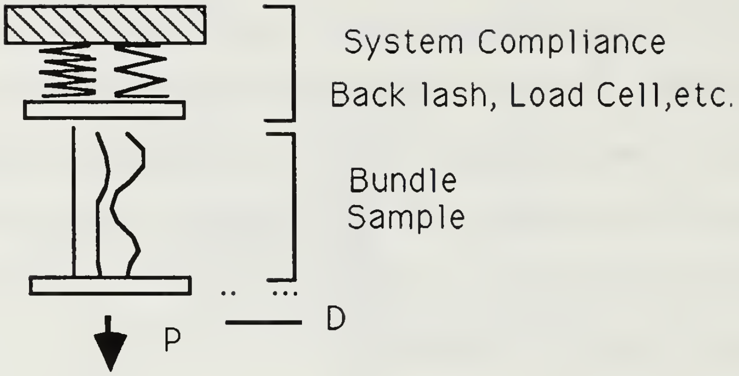


Figure 45

INSTRON Testing Machine Equivalent Model

With the spring in series model, the total displacement of the system due to a load is equal to Equation 24. The load due to the fibers is Equation 25 and the load due to compliance is equation 26.

$$\delta_t = \delta_f + \delta_c = P/(K_f + K_c) \tag{24}$$

$$\delta_f = P/K_f \tag{25}$$

$$\delta_c = P/K_c \tag{26}$$

where δ_t = total bundle displacement

δ_f = fiber displacement

δ_c = compliance displacement

K_f = fiber stiffness coefficient

K_c = compliance stiffness coefficient

Equations 25 and 26 demonstrate that the fiber and compliance displacements are functions of load. If the stiffness coefficients and the load are known, then the displacement due to the fibers may be found by Equation 27. It is important to note that the stiffness coefficients for the fibers and the compliance are likely to be nonlinear. The fiber nonlinearity is primarily due to the slack in the early displacement. The compliance will be nonlinear due to the physical processes that contribute to form the compliance. Many of these processes are directional in nature.

$$\delta(P)_f = \delta(P)_t - \delta(P)_c \tag{27}$$

From Equation 27, the typical bundle test graph in Figure 1 may now be represented as Figure 46 with the compliance displacement being subtracted from the fiber displacement.

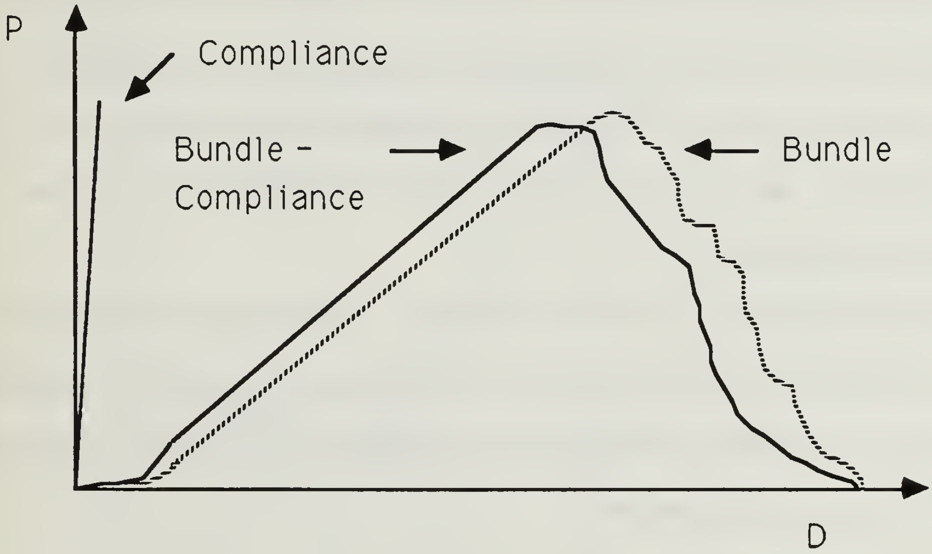


Figure 46

Typical Bundle Test Load vs Displacement Graph Compliance and Fiber Displacement Separated

To determine the fiber displacement, a means to subtract the compliance displacement is required. An equation must be determined to fit $\delta(P)_c$ to implement Equation 27.

If K_c were linear, it would be a simple matter to solve for the $\delta(P)_c$ function. However, as mentioned above, the function will not be linear. Because of this, $\delta(P)_c$ must be measured by experimentation. The data must then be curve-fit to form a continuous function; this function may then be used to implement Equation 27.

B. COMPLIANCE TESTING

From the model illustrated in Figure 45, a means to eliminate the displacement of the fibers would be to set the gauge length of the bundle to zero. The fibers may not be eliminated because the gripping mechanism to hold the bundle in place is a part of the compliance, but the gauge length can be brought very nearly to zero. To do this, a sample is prepared like the one shown in Figure 47. If there are no fibers that displace, all of the displacement recorded must be due to machine compliance.

To measure $\delta(P)_c$, a bundle test is completed with the 0 gauge length sample in accordance with the procedures outlined in Appendix D. A typical INSTRON compliance test load vs. displacement graph is shown as Figure 48.

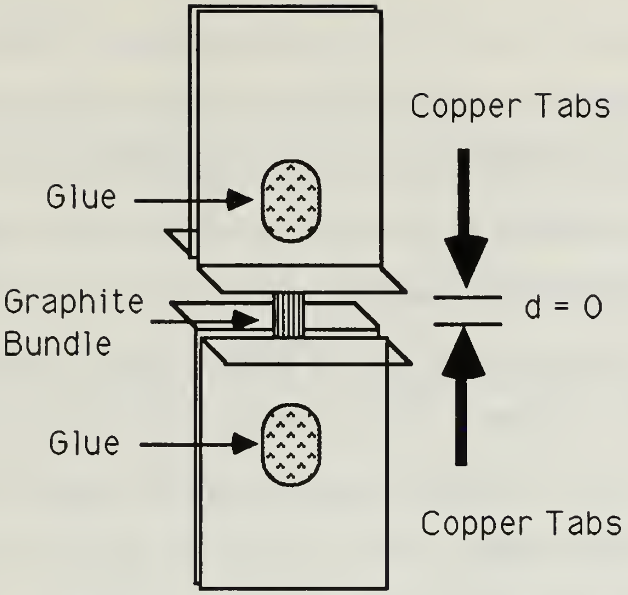


Figure 47

0 Gauge Length Sample Used to Test Compliance

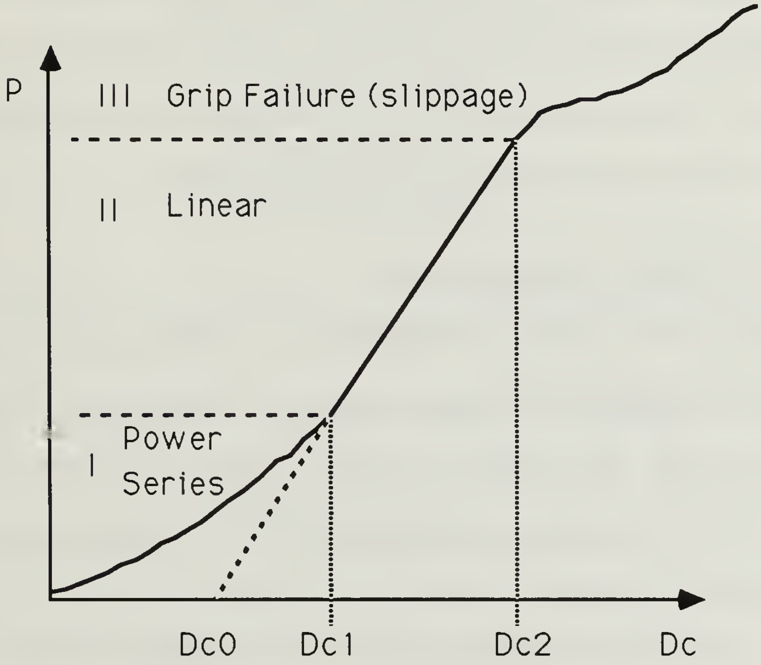


Figure 48

INSTRON Compliance Test Load vs. Displacement Graph

The first region, 0 to Dc1, is very nonlinear. This is due to the directional compliance in the INSTRON as the displacement is first applied. Physical processes include the backlash in the gears, nonlinear friction and damping as the gears and clutches engage, and noise below the sensitivity of the load cell.

Region two, Dc1 to Dc2, is the linear region. The compliance in this region is due to linear spring tension of the machine as modeled in Figure 44. The K is very high, which is expected for a testing machine. It should be high so that the load it absorbs is very low when compared to the load being absorbed by the sample.

Region three is nonlinear. It is believed that in this region the grips are beginning to fail and that the fibers are actually slipping between the copper tabs. The data in this region does not reflect the machine compliance and is not utilized in the analysis. It is assumed, however, that if the sample had not slipped the compliance curve would have continued, extending the linear region.

C. CURVE-FITTING PROCEDURE

The fitting of a curve to approximate $P(\delta)_c$ was completed by separating the function into two regions, selecting a power series model, Equation 28, for region I, a linear model; Equation 29, for section II; and setting boundary conditions at Dc1, Equations 30 and 31.

$$\text{for } 0 < Dc < Dc1 \qquad Dc = A1(P)n + A2 \tag{28}$$

$$\text{for } Dc1 < Dc \qquad Dc = A3P + A4 \tag{29}$$

Boundary Conditions

$$\text{(1) } Dc1 \text{ (Equation 28)} = Dc1 \text{ (Equation 29)} \qquad (30)$$

$$\text{(2) } Dc1' \text{ (Equation 28)} = Dc1' \text{ (Equation 29)} \qquad (31)$$

If Dc2 and Dc1 are known, then from Equation 29 for region two:

$$A_3 = Dc2 - Dc1/P_1 - p(Dc1) \qquad (32)$$

$$A_4 = -A_3P_1 + Dc1 \qquad (33)$$

From Equations 28, 29, and 31, an equation for A_1 can be derived:

$$\partial\, Dc/\partial\, P = nA_1(P)^{n-1}$$

$$\partial\, Dc/\partial\, P = A_3$$

$$A_3 = nA_1(P)^{n-1}$$

$$A_1 = A_3/n\ (P_1)^{n-1} \qquad (34)$$

From Equations 29, 30, and 34, an equation for A2 can be derived:

$$Dc1 = ((A_3/n\ (Dc1 - Dc0)^{n-1}) * (Dc1 - Dc0)^n/A_3 + A_2$$

$$A_2 = Dc_1 - A_3P_1/n \qquad (35)$$

This gives us five unknowns and four equations. Equations 32 and 33 can be solved directly from information gained from the 0 gauge length data. Equations 34 and 35 are coupled by n, so A_3 and A_4 may be solved for by optimizing the variable n. To optimize n, an error function is created and its derivative is taken and then summed for all the data points between zero and Dc1 for different values of n. When the error function is minimized to approximately zero, n is known. The n can then be substituted into equations 13 and 14 to yield the constants A_3 and A_4.

Substituting Equations 32 and 33 into Equation 28 gives Equation 36.

$$Dc(P) = (A_3P_1/n) * ((P/P_1)^{n-1}) + Dc1 \tag{36}$$

$$\begin{aligned} \partial\, Dc(P_i)/\partial\, N = {} & (A_3P_1/n) * \ln(P/P_1) * (P/P_1)^n \\ & + A_3P_1n^{-2}(1 - (P/P_1)^n) \end{aligned} \tag{37}$$

The error function becomes

$$H(n) = \sum (Dc(P_i) - D_i)\ \partial\, Dc(P_i)/\partial\, N \tag{38}$$

for i = 1,2,3 ... number of data points from 0 to Dc1. Equation 38 is then iterated until H(n) goes to zero (.0000).

The process of solving for the coefficients is greatly enhanced by the use of spreadsheets and microcomputers. Programs such as Lotus 1-2-3 and Microsoft Excel allow the user to import the data directly into a spreadsheet and manipulate the data. The results for the INSTRON compliance used in this project were found using Lotus 1-2-3.

A Fortran program is in development to solve this procedure but is not functional at this time.

APPENDIX D

BUNDLE TESTING

The failure load for graphite bundles was determined with the use of the Instron Universal Testing Instrument Model 4206 (INSTRON) and associated IBM INSTRON control software, version 4.01. The fiber strength statistics were found by removing the compliance displacement with the software developed in this appendix. The compliance displacement function was approximated by the curve fit detailed in Appendix C. The modified data was then used with software developed by Lt. Joseph Schmidt to determine the fiber parameters α and β for the given gauge length.

All testing was completed in the Advanced Composites Laboratory, Naval Postgraduate School, Monterey. Laboratory Technician Mr. Jim Nageotte and Professor Edward Wu assisted with the preparation of samples and the testing.

A. BUNDLE TESTING PROCEDURE

The testing was completed in accordance with the following procedure.

- Turn on INSTRON and allow 60 minutes to warm up.
- Calibrate the INSTRON in accordance with posted procedures for mechanical and electrical calibration (only required for first test of the day).
- Turn on attached IBM AT and enter INSTRON test software. From C prompt, type: MT\DATA\MT <enter>
- Load sample into machine.

- Ensure sample is vertically aligned correctly; adjust if necessary.
- Set zero load level.
  - Depress Load Bal button and then enter on the INSTRON.
- Set cross-head speed to .2 mm/min.
- Set gauge length.
  - Run cross-head up until a load of .2 ±.02 kg is achieved.
  - Depress Gauge Length button on the INSTRON.
  - Run cross-head down until a load of zero is achieved.
  - Run cross-head up until a load of .2 ±.02 kg is achieved.
  - Extension should read 0.0. If it does not, repeat all steps.
  - Run cross-head down until a load of zero is achieved.
  - Depress jog down switch twice.
  - Depress Gauge Length button.

    *(Crosshead Speed may be adjusted if necessary)
- Select appropriate test method.
- Enable IEEE interface.
  - Depress IEEE button on the INSTRON.
- Run the test.
- Plot the results.
- Plot on HP plotter using Plot option in INSTRON software.
- Put data into ASCII file.
- Dump data to hard disk or floppy disc using Utilities option in INSTRON software.
- Exit INSTRON software.
- Remove Compliance displacement.
- Rename test data file to TEST.DAT and put onto floppy disk.
- Place data disk in drive B:

- Place compliance removal program disk in drive A:
- Type T5 <enter>

The disk in drive B: now contains the data with compliance removed and the data with compliance not removed. The data is now ready to be run in the software developed by Lt. Joseph Schmidt that will retrieve the fiber parameters α and β.

B. PROGRAM LISTING

The compliance removal program "program T5" takes the five coefficients for the curve fit compliance function and then for the corresponding load subtracts the displacement from the data due to compliance. The method for determining the compliance curve fit coefficients is detailed in Appendix C.

The program is written in Microsoft Fortran 4.01. It will run on any IBM/compatible personal computer. To operate the program, place the program disk into the A: drive. The data disk must be placed into the B: drive. When this is completed, type: T5 <enter>.

PROGRAM T5

SUBROUTINE LISTING:

INIT	Initializes arrays to zero
LOAD	Opens the data file and reads in the machine data
CONVERT	Converts machine data into SI units
REMCON	• Prompts the user to input the compliance curve coefficients • Removes the displacement from the data due to compliance

OUTPUT	Writes to the B: drive the modified data

VARIABLE LISTING:

DDISP(6000)	Test displacement data
DLOAD(6000	Test load data
INDEX	Test data point counter
XCONV	Displacement conversion factor
YCONV	Load conversion factor
A1	Compliance curve coefficient
A2	Compliance curve coefficient
N	Compliance curve coefficient
A3	Compliance curve coefficient
A4	Compliance curve coefficient
DC1	Transition displacement between two curve fit equations
ZERO	Noise level of load cell

```
      PROGRAM T5
************************************************************************
*   PROGRAM T5                                                        *
*                                                                     *
*   THIS PROGRAM WILL TAKE INSTRON 4200 SERIES BUNDLE RAW DATA OUTPUT *
*   AND ALLOW THE USER TO CONVERT THE DATA INTO DESIRED UNITS AND TO  *
*   TO REMOVE MACHINE COMPLIANCE DISPLACEMENT.  THE INPUT DATA FILE   *
*   MUST BE PLACED IN THE B- DRIVE.  THE INPUT DATA FILE MUST BE      *
*   NAMED TEST.DAT.  A MAXIMUM OF 6000 DATA POINTS IS ALLOWED.  TO    *
*   EXECUTE THE PROGRAM, PLACE THE PROGRAM DISK IN THE A DRIVE,       *
*   TYPE A-T5 AND HIT ENTER.  tHE USER SHOULD THEN FOLLOW THE SCREEN  *
*   PROMPTS.                                                          *
*             THE REQUIRED INPUTS ARE-                                *
*           -  NUMBER OF DATA POINTS                                  *
*           -  CONVERSION FACTOR FOR LOAD AND DISPLACEMENT            *
*           -  COMPLIANCE CURVE PARAMATERS (IF DESIRED)               *
*                                                                     *
*   THE OUTPUT DATA FILE WILL BE PUT ON THE DISK IN THE B DRIVE AS    *
*   FILE EXPER.OUT.   A SUMMARY PRINTOUT OF THE INPUT IS PLACED ON    *
*   THE DISK IN THE B DRIVE AS DATCON.PRT .                           *
*                                                                     *
************************************************************************
      REAL XCONV,YCONV,A1,A2,A3,A4,N,DDISP(6000),DLOAD(6000),
     +ZERO
      INTEGER I,J,DP,INDEX(6000),Q
      PRINT*,'*** RUNNING PROGRAM T5 ***'
      PRINT*
*  CALL SUBROUTINE INIT TO INITIALIZE ARRAYS
      CALL INIT(DDISP,DLOAD,INDEX,XCONV,YCONV)
*  CALL SUBROUTINE LOAD TO LOAD IN DATA INTO PROGRAM
      CALL LOAD(DDISP,DLOAD,INDEX,DP)
*  ALLOW USER TO CONVERT DATA INTO DESIRED UNITS
      PRINT*,'    DO YOU NEED TO CONVERT DATA INTO [SI] UNITS'
      PRINT*,' THIS SHOULD ONLY BE REQUIRED FOR MACHINE TEST DATA'
      PRINT*,'        IF YES TYPE 1, ELSE TYPE 0 TO CONTINUE'
      READ*,Q
      IF(Q .EQ. 1) THEN
*  IF USER DESIRES TO CONVERT UNITS CALL SUBROUTINE CONVERT TO CONVERT
*  DATA
      CALL CONVERT(XCONV,YCONV,DP,DDISP,DLOAD)
      ENDIF
*  CALL SUBROUTINE REMCOM TO REMOVE COMPLIANCE FROM DATA
      CALL REMCOM(DDISP,DLOAD,A1,A2,A3,A4,N,DP,ZERO,DC1)
*  CALL SUBROUTINE OUTPUT TO OUTPUT DATA INTO DATA FILES ON DISK B
      CALL OUTPUT(INDEX,DDISP,DLOAD,A1,A2,A3,A4,N,DP,ZERO,XCONV,YCONV,
     +DC1)
      PRINT*,'*** END OF PROGRAM ***'
      END
************************************************************************
*  SUBROUTINE INIT                                                    *
*                                                                     *
*  THIS PROGRAM WILL INITIALIZE THE DATA ARRAYS, INDEX AND CONVERSION *
*  FACTORS PRIOR TO INPUTING NEW DATA.                                *
*                                                                     *
************************************************************************
      SUBROUTINE INIT(DDISP,DLOAD,INDEX,XCONV,YCONV)
      REAL DDISP(6000),DLOAD(6000),XCONV,YCONV
      INTEGER INDEX(6000)
*  PRINT HEADER
      PRINT*, '*** RUNNING SUBROUTINE INIT ***'
      PRINT*
*  RUN LOOP TO SET DATA ARRAY INDEX, DDISP AND DLOAD TO 0
      DO 10 I = 1,6000
      INDEX(I) = 0
      DDISP(I) = 0.
      DLOAD(I) = 0.
   10 CONTINUE
*  SET CONVERSION FACTORS TO 1.0
      XCONV = 1.
      YCONV = 1.
      END
************************************************************************
*   SUBROUTINE LOAD                                                    *
*                                                                      *
*   SUBROUTINE LOAD WILL OPEN DATA FILE B-TEST.DAT AND READ IN THE     *
*   DATA WITH AN UNFORMATTED READ STATEMENT.  THE NUMBER OF DATA       *
*   POINTS (DP) TO BE READ MUST BE ENTERED CORRECTLY OR PROGRAM WILL   *
*   ERROR OUT IN THIS SUBROUTINE.                                      *
************************************************************************
      SUBROUTINE LOAD(DDISP,DLOAD,INDEX,DP)
      REAL DDISP(6000),DLOAD(6000)
      INTEGER I,DP,INDEX(6000)
*  PRINT HEADER
      PRINT*,'*** RUNNING SUBROUTINE LOAD ***'
      PRINT*
*  OPEN DEVICE 15, FILE B-TEST.DAT
      OPEN(15,FILE='B-TEST.DAT')
*  INPUT NUMBER OF DATA POINTS (DP)
      PRINT*,'INPUT NUMBER OF DATA ELEMENTS TO BE READ'
      PRINT*,'  @@@ MAXIMUM INPUT VALUE IS 6000 @@@'
      READ*,DP
*  RUN LOOP TO READ IN DATA POINTS INDEX, DDISP AND LOAD
      DO 10 I = 1,DP
      READ(15,*)INDEX(I),DDISP(I),DLOAD(I)
   10 CONTINUE
*  CLOSE DEVICE 15
      CLOSE (15)
      END
************************************************************************
*  SUBROUTINE CONVERT                                                  *
*                                                                      *
*  SUBROUTINE CONVERT WILL CONVERT THE DATA FROM FILE TEST.DAT INTO    *
*  WHICHEVER UNITS THE USER DESIRES.  THE USER MUST INPUT CONVERSION   *
*  FACTORS WHICH WILL BE DIVIDED FROM THE ORIGINAL DATA.  THE X CONV   *
*  CORRESPONDS TO DISPLACEMENT AND THE Y CONV CORRESPONDS TO LOAD OR   *
*  FORCE.  IF NO CONVERSION IS DESIRED, ENTER 1 FOR THE CONVERSION     *
*  FACTORS.                                                            *
************************************************************************
      SUBROUTINE CONVERT(XCONV,YCONV,DP,DDISP,DLOAD)
      REAL DDISP(6000),DLOAD(6000),XCONV,YCONV
      INTEGER I,DP
*  PRINT HEADER
```

```
      PRINT*,'*** RUNNING SUBROUTINE CONV ***'
      PRINT*
      PRINT*, 'PROGRAM T5 WILL CONVERT DATA INTO [SI] UNITS'
      PRINT*
*  INPUT X OR DISPLACEMENT CONVERSION FACTOR
      PRINT*,'INPUT X CONVERSION  (DISPLACEMENT)'
      READ*, XCONV
*  INPUT Y OR LOAD/FORCE CONVERSION FACTOR
      PRINT*,'INPUT Y CONVERSION  (LOAD/FORCE)'
      READ*, YCONV
*  CONVERT DATA
      DO 10 I = 1,DP
      DDISP(I) = DDISP(I)/XCONV
      DLOAD(I) = DLOAD(I)/YCONV
   10 CONTINUE
      END
************************************************************************
*  SUBROUTINE REMCON                                                   *
*                                                                      *
*  SUBROUTINE REMCON WILL IF THE USER DESIRES REMOVE THE MACHINE       *
*  COMPLIANCE DISPLACEMENT FROM THE DATA.  THE USER MUST INPUT THE     *
*  COMPLIANCE CURVE PARAMETERS AND THE DATA ZERO LOAD LEVEL.           *
*  THE USER SHOULD TAKE CARE TO ENSURE THE COMPLIANCE PARAMETERS ARE   *
*  THE SAME UNITS AS THE CONVERSION FACTORS.                           *
************************************************************************
      SUBROUTINE REMCOM(DDISP,DLOAD,A1,A2,A3,A4,N,DP,ZERO,DC1)
      REAL DDISP(6000),DLOAD(6000),A1,A2,A3,A4,N,ZERO,DC1
      INTEGER I,DP,Q
*  PRINT HEADER
      PRINT*,'*** RUNNING SUBROUTINE REMCOM ***'
      PRINT*
*  ALLOW USER TO REMOVE COMPLIANCE FROM THE DATA
      PRINT*,'DO YOU DESIRE TO REMOVE THE MACHINE COMPLIANCE FROM THE DA
     +TA'
      PRINT*,'IF YES TYPE 1, ELSE TYPE 0 TO CONTINUE'
      READ*,Q
      IF(Q .EQ. 1) THEN
*  IF USER DESIRES TO REMOVE COMPLIANCE, INPUT COMPLIANCE PARAMETERS
      PRINT*,'INPUT COMPLIANCE CURVE COEFFICIENTS'
      PRINT*,'INPUT A1'
      READ*,A1
      PRINT*,'INPUT A2'
      READ*,A2
      PRINT*,'INPUT N'
      READ*,N
      PRINT*,'INPUT A3'
      READ*,A3
      PRINT*,'INPUT A4'
      READ*,A4
      PRINT*,'INPUT DC1'
      READ*,DC1
      PRINT*,'INPUT ZERO NOISE LEVEL (LOAD IN KG)'
      READ*,ZERO
*  REMOVE COMPLIANCE DISPLACEMENT FROM THE DATA
      PRINT*
      PRINT*,'*** REMOVING MACHINE COMPLIANCE FROM DATA ***'
      PRINT*
      DO 100 I = 1,DP
*   DETERMINE IF DISPLACEMENT DATA IS IN COMPLIANCE POWER CURVE OR
*   LINEAR REGION AND SUBRTRACT CORRECT AMOUNT OF DISPLACEMENT
      IF(DLOAD(I) .LT. ZERO) THEN
      GOTO 99
      ENDIF
      IF(DDISP(I) .LT. DC1) THEN
      DDISP(I) = DDISP(I) - ((A1*(DLOAD(I)**N)) + A2)
      ELSE
      DDISP(I) = DDISP(I) - ((A3*DLOAD(I)) + A4)
      ENDIF
   99 CONTINUE
  100 CONTINUE
      ENDIF
      CONTINUE
      END
*****************************************************************************
*   SUBROUTINE OUTPUT                                                       *
*                                                                           *
*   SUBROUTINE OUTPUT WILL WRITE THE DATA TO FILE EXPER.OUT.  IT WILL       *
*   ALSO CREATE A DATA SUMMARY FILE AS DATCON.PRT .  THE OUTPUT FILES       *
*   ARE PLACED ONTO THE DISK IN THE B DRIVE.                                *
*****************************************************************************
      SUBROUTINE OUTPUT(INDEX,DDISP,DLOAD,A1,A2,A3,A4,N,DP,ZERO,XCONV,
     +YCONV,DC1)
      REAL DDISP(6000),DLOAD(6000),A1,A2,A3,A4,N,ZERO,XCONV,YCONV
      INTEGER I,DP,INDEX(6000),Q
*   PRINT HEADER
      PRINT*,'*** RUNNING SUBROUTINE OUTPUT ***'
      PRINT*
   10 PRINT*,'DATA WILL BE OUTPUT TO FILE B-EXPER.OUT'
*   PROMPT USER TO PLACE TARGET DATA DISK IN DRIVE B-
      PRINT*,'ENSURE A DISK WITH SUFFICIENT SPACE IS IN DRIVE B-'
      PRINT*,'TYPE 1 TO CONTINUE'
      READ*,Q
      IF(Q .NE. 1) GOTO 10
*   OPEN DEVICE 12 AND WRITE DATA TO FILE B-EXPER.OUT
      OPEN(12, FILE='B-EXPER.OUT')
      DO 100 I = 1,DP
      WRITE(12,900)INDEX(I),DDISP(I),DLOAD(I)
  100 CONTINUE
*   CLOSE DEVICE 12
      CLOSE(12)
*   ALLOW USER TO CREATE A DATA SUMMARY FILE
      PRINT*,'DO YOU DESIRE A SUMMARY PRINTOUT FOR THE DATA CONVERSION'
      PRINT*,'IF YES TYPE 1, ELSE TYPE 0 TO EXIT'
      READ*,Q
*   IF USER DESIRES DATA SUMMARY FILE, OPEN DEVICE 12 AND WRITE
*   PARAMETERS TO FILE DATCON.PRT
      IF(Q .EQ. 1) THEN
      OPEN(12, FILE='B-DATCON.PRT')
      WRITE(12,910)
      WRITE(12,911)DP,XCONV,YCONV
      WRITE(12,912)ZERO,DC1
      WRITE(12,913)A1,A2,N,A3,A4
      CLOSE(12)
      ENDIF
      CONTINUE
*  WRITE FORMAT STATEMENTS
  900 FORMAT(  I6,1X,F9.4,1X,F9.4)
  910 FORMAT(  'COMPLIANCE REMOVAL DATA CONVERSION COEFFICIENTS',//)
  911 FORMAT(  'NUMBER OF DATA POINTS',8X,I7/
     1         'X CONVERSION FACTOR  ',5X,F10.7/
     2         'Y CONVERSION FACTOR  ',5X,F10.7//)
  912 FORMAT(  'ZERO NOISE LEVEL (KG)',10X,F7.4/
     1         'DC1 -LINEAR SECTION- ',8X,F9.4//)
  913 FORMAT(  'COMPLIANCE CURVE COEFFICIENTS'//
     1         'POWER FACTOR PORTION'//
     2         'A1 =   ',F6.4/
     3         'A2 =   ',F6.4/
     4         ' N =   ',F6.4/
     5         'LINEAR PORTION'//
     6         'A3 =   ',F6.4/
     7         'A4 =   ',F6.4/)
      END
```

APPENDIX E

TEST DATA

A. COMPLIANCE TEST DATA

The INSTRON compliance test data forms are contained in this appendix. They are tabulated in Test Number sequence. The raw data is stored on the IBM AT personal computer in the Composites Laboratory, Naval Postgraduate School, in director MT/DATA/ as file (Test Number).MAD.

```
                              NPS Composites Lab
                              U.S.Naval Postgraduate School
                              Monterey, CA

Fiber Bundle Compliance Curve
Zero guage length
.15 mm/min

Test type:     Compliance Curve                             Instron Corporation
                                                            Series IX Automated Materials Testing System v4.01c
Operator name: Jim                                          Test Date: August  5,1988

Sample Identification: OGL10508                             Sample Type:   bndl
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):  10.00                          Humidity ( % ):    60
     Crosshead Speed (mm/min ):    .150                     Temperature (deg. F):    70

Dimensions:
                               Spec. 1

    Lin. Density (den)       2036.0
    Gauge length (mm)          1.0000

Out of  1 specimens,  0 excluded.

                                       Load     Displcment  % Strain  Displcment    Load
                             Modulus    at         at          at         at         at
         Specimen   label?            Maximum     Break      Break     Maximum    Maximum
         Number             (gm/den)    (Kg)      (mm)        (%)        (mm)       (Kg)
         -----------------------------------------------------------------------------------

             1      good     99.95     29.57      .3011      30.11      .2942      29.57


         Mean:               99.95     29.57      .3011      30.11      .2942      29.57

         Standard
         Deviation:        ---------- ---------- ---------- ---------- ---------- ----------

         Mean -
         2.00 * Sdv:       ---------- ---------- ---------- ---------- ---------- ----------

         Mean +
         2.00 * Sdv:       ---------- ---------- ---------- ---------- ---------- ----------

         Minimum:            99.95     29.57      .3011      30.11      .2942      29.57

         Maximum:            99.95     29.57      .3011      30.11      .2942      29.57
```

```
  VERSION  4.01c
    Sample id : OCL10508                         Test date : August  5,1988
      Version : 4.01c                         Version date : 06/09/88
 Report file# : 34                                Operator : Jim

 X conversion :   .03937008                   X A/D offset :             .0000
 Y conversion :  2.20462300                   Y A/D offset :             .0000

  Sample rate :  10.00                        Extensometer : NO
    A/D range :   0                              Autostart : OFF
   Calib type : AUTOMATIC                         Geometry : CYLINDRICAL
   Calib load :       110.2311                Calib extens :           .0000
  Temperature :  70                               Humidity : 60
    Test type : DENIER                         # specimens :   1
     Bar type : bndl                          Entry dimens : YES
  Break check :   100.00000                   Thresh delay :         .02205
   Load limit :   110.23110                   Extens limit :         .15748

 Sample dimensions :
 A:        .0394   B:  2036.0000    C:        .0394    D:        .0394    E: NO
------------------------------------------------------------------------------
   Specimen # :       1                       Stop coll. status : BREAK DETECT
 Maximum load :       65.191                  Max load point #  :        1286
   Max extens :         .013                  Max extens pnt #  :        1309

 Number of elements :  1309

 Specimen dimensions :
A:       .0393701 B:  2036.0000000 C:       .0393701 D:       .0393701 E:NO


 Auxiliary Input Array # 1
******* ******* ******* ******* ******* ******* ******* ******* *******
 Auxiliary Input Array # 2
******* ******* ******* ******* ******* ******* ******* *******       .01
------------------------------------------------------------------------------
```

B. BUNDLE TEST DATA

The INSTRON bundle test data forms are contained in this appendix. They are tabulated in Test Number sequence. The raw data is stored on the IBM AT personal computer in the Composites Laboratory, Naval Postgraduate School, in directory MT\DATA\ as file (Test Number).MAD.

```
                         COMPOSITES LABORATORY
                         NAVAL POSTGRADUATE SCHOOL
                         MONTEREY  CA  93940

GRAPHITE BUNDLE TEST METHOD  (70 CM)
Test method for Instron 4206.  Used for testing AS-4
Graphite bundles (appx 1000 fibers)

Test type:     OIL BUNDLE                           Instron Corporation
                                                    Series IX Automated Materials Testing System v4.01c
Operator name: MARK JONES                           Test Date: September  8,1988

Sample Identification: 080901                       Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):   6.67                  Humidity ( % ):    50
     Crosshead Speed (mm/min ):   7.000             Temperature (deg. F):    73


'BATCH ID'          080901  70 CM WITH OIL

Dimensions:
                                  Spec. 1

    Lin. Density (tex)          2036.0
    Gauge length (mm)             700.00

Out of  1 specimens,  0 excluded.

                              Displcment  % Strain    Load
                                  at         at        at
                  Specimen     Maximum    Maximum    Maximum
                  Number         (mm)       (%)        (kN)
                  ----------------------------------------------
                      1        5.240      .7486      .1359


                  Mean:        5.240      .7486      .1359

                  Standard
                  Deviation:  ---------- ---------- ----------
```

```
                         COMPOSITES LABORATORY
                         NAVAL POSTGRADUATE SCHOOL
                         MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (5 CM)


Test type:      Yarn/Fiber                            Instron Corporation
                                                      Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                             Test Date: September  9,1988

Sample Identification: 090901                         Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):   3.33                    Humidity ( % ):    50
     Crosshead Speed (mm/min ):    .500               Temperature (deg. F):    73


'BATCH ID'          090901
'OIL OR NO OIL'     NO OIL

Dimensions:
                              Spec., 1

    Lin. Density (tex)       2036.0
    Gauge length (mm)          50.000

Out of  1 specimens,  0 excluded.

                                   Displcment  % Strain     Load
                                       at         at          at
                           Specimen  Maximum    Maximum    Maximum
                           Number     (mm)        (%)        (KN)
                           ---------------------------------------------
                              1      .6500      1.300      .2349


                           Mean:     .6500      1.300      .2349

                           Standard
                           Deviation: ---------- ---------- ----------


                           Mean -
                           2.00 * Sdv: ---------- ---------- ----------

                           Mean +
                           2.00 * Sdv: ---------- ---------- ----------

                           Minimum:   .6500      1.300      .2349

                           Maximum:   .6500      1.300      .2349
```

```
 VERSION  4.01c
   Sample id : 090901                        Test date : September  9,1988
     Version : 4.01c                      Version date : 06/09/88
Report file# : 12                             Operator : Mark Jones

X conversion :   .03937008                X A/D offset :             .0000
Y conversion :  2.20462300                Y A/D offset :             .0000

 Sample rate :   3.33                     Extensometer : NO
   A/D range :   0                           Autostart : OFF
  Calib type : AUTOMATIC                      Geometry : CYLINDRICAL
  Calib load :      110.2311              Calib extens :           .0000
 Temperature :  73                            Humidity : 50
   Test type : DENIER                      # specimens :  1
    Bar type : AS-4                       Entry dimens : YES
 Break check :     10.00000               Thresh delay :       .22481
  Load limit :   112.40450                Extens limit :       .09843

Sample dimensions :
A:       .0394   B: 18324.0000   C:      1.9685   D:       .0394   E: NO
------------------------------------------------------------------------
  Specimen # :       1                    Test end status :   10
Maximum load :      52.762                Max load point #  :          260
  Max extens :        .047                Max extens pnt #  :          483

Number of elements :   483

Specimen dimensions :
A:       .0393701 B: 18324.0000000 C:      1.9685040 D:      .0393701 E:NO

Auxiliary Input Array # 1
******* ******* ******* ******* ******* ******* ******* ******* *******
Auxiliary Input Array # 2
******* ******* ******* ******* ******* ******* ******* ******* *******
-------------------------------------------------------------------------
```

```
                              COMPOSITES LABORATORY
                              NAVAL POSTGRADUATE SCHOOL
                              MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (.5 CM)



Test type:      Yarn/Fiber                                   Instron Corporation
                                                             Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                                    Test Date: September  9,1988

Sample Identification: 090902                                Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):    .33                           Humidity ( % ):    50
     Crosshead Speed (mm/min ):    .050                      Temperature (deg. F):    73


'BATCH ID'          090902
'OIL OR NO OIL'     NO OIL

Dimensions:
                               Spec. 1

    Lin. Density (tex)        2036.0
    Gauge length (mm)            5.0000

Out of  1 specimens,  0 excluded.

                                 Displcment   % Strain      Load
                                     at          at          at
                              Specimen   Maximum     Maximum     Maximum
                              Number       (mm)        (%)       , (KN)
                              ---------------------------------------------
                                  1      .2500       5.000       .2034


                              Mean:      .2500       5.000       .2034

                              Standard
                              Deviation: ----------  ----------  ----------

                                  .
                              Mean -
                              2.00 * Sdv: ----------  ----------  ----------

                              Mean +
                              2.00 * Sdv: ----------  ----------  ----------

                              Minimum:   .2500       5.000       .2034

                              Maximum:   .2500       5.000       .2034
```

```
                         COMPOSITES LABORATORY
                         NAVAL POSTGRADUATE SCHOOL
                         MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (.5 CM)


Test type:      Yarn/Fiber                                  Instron Corporation
                                                            Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                                   Test Date: September  9,1988

Sample Identification: 090903                               Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):     .33                         Humidity ( % ):    50
     Crosshead Speed (mm/min ):     .050                    Temperature (deg. F):    73


'BATCH ID'          090903
'OIL OR NO OIL'     NO OIL

Dimensions:
                              Spec. 1

    Lin. Density (tex)      2036.0
    Gauge length (mm)         5.0000

Out of  1 specimens,  0 excluded.
Sample comments: Maximum Load 22.36 kg  Relaxtaion Load to 21.33 kg

                              Displcment  % Strain    Load
                                 at          at        at
                   Specimen    Maximum     Maximum   Maximum
                   Number       (mm)        (%)       (KN)
                   ---------------------------------------------
                       1       .2500       5.000      .2194


                   Mean:       .2500       5.000      .2194

                   Standard
                   Deviation: ----------  ---------- ----------


                   Mean -
                   2.00 * Sdv: ----------  ---------- ----------

                   Mean +
                   2.00 * Sdv: ----------  ---------- ----------

                   Minimum:    .2500       5.000      .2194

                   Maximum:    .2500       5.000      .2194
```

```
                                COMPOSITES LABORATORY
                                NAVAL POSTGRADUATE SCHOOL
                                MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (.5 CM)


Test type:      Yarn/Fiber                                Instron Corporation
                                                          Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                                 Test Date: September  9,1988

Sample Identification: 090904                             Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):    .33                        Humidity ( % ):    50
     Crosshead Speed (mm/min ):    .050                   Temperature (deg. F):    73


'BATCH ID'           090904
'OIL OR NO OIL'      NO OIL

Dimensions:
                                 Spec. 1

    Lin. Density (tex)          2036.0
    Gauge length (mm)             5.0000

Out of  1 specimens,  0 excluded.
Sample comments: Specimin is slipping and test stopped at .46 mm

                             Displcment  % Strain     Load
                                 at         at          at
                  Specimen    Maximum    Maximum    Maximum
                  Number        (mm)       (%)        (KN)
                  ---------------------------------------------
                      1       .2700      5.400      .2357


                  Mean:       .2700      5.400      .2357

                  Standard
                  Deviation: ----------  ----------  ----------


                  Mean -
                  2.00 * Sdv: ----------  ----------  ----------

                  Mean +
                  2.00 * Sdv: ----------  ----------  ----------

                  Minimum:    .2700      5.400      .2357

                  Maximum:    .2700      5.400      .2357
```

```
                           COMPOSITES LABORATORY
                           NAVAL POSTGRADUATE SCHOOL
                           MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (.5 CM)



Test type:      Yarn/Fiber                                    Instron Corporation
                                                              Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                                     Test Date: September  9,1988

Sample Identification: 090905                                 Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):    .33                            Humidity ( % ):    50
     Crosshead Speed (mm/min ):    .050                       Temperature (deg. F):    73


'BATCH ID'          090905
'OIL OR NO OIL'     NO OIL

Dimensions:
                                 Spec. 1

    Lin. Density (tex)         2036.0
    Gauge length (mm)            5.0000

Out of  1 specimens,  0 excluded.
Sample comments: Sample slipped

                                 Displcment   % Strain     Load
                                     at          at          at
                      Specimen    Maximum     Maximum     Maximum
                      Number        (mm)        (%)         (kN)
                      ---------------------------------------------
                          1       .2900       5.800       .2992


                      Mean:       .2900       5.800       .2992

                      Standard
                      Deviation: ----------  ----------  ----------


                      Mean -
                      2.00 * Sdv: ----------  ----------  ----------

                      Mean +
                      2.00 * Sdv: ----------  ----------  ----------

                      Minimum:    .2900       5.800       .2992

                      Maximum:    .2900       5.800       .2992
```

```
                                   COMPOSITES LABORATORY
                                   NAVAL POSTGRADUATE SCHOOL
                                   MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (.5 CM)


Test type:      Yarn/Fiber                                     Instron Corporation
                                                               Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                                      Test Date: September  9,1988

Sample Identification: 090906                                  Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):    .33                             Humidity ( % ):    50
     Crosshead Speed (mm/min ):    .050                        Temperature (deg. F):    73


'BATCH ID'          090906
'OIL OR NO OIL'     NO OIL

Dimensions:
                                   Spec. 1

    Lin. Density (tex)           2036.0
    Gauge length (mm)              5.0000

Out of  1 specimens,  0 excluded.
Sample comments: SAMPLE SLIPPED

                                       Displcment   % Strain    Load
                                           at          at         at
                                Specimen   Maximum     Maximum    Maximum
                                Number      (mm)        (%)        (KN)
                                ----------------------------------------------
                                   1       .2400       4.800      .2664


                                Mean:      .2400       4.800      .2664

                                Standard
                                Deviation: ----------  ---------- ----------


                                Mean -
                                2.00 * Sdv: ---------- ---------- ----------

                                Mean +
                                2.00 * Sdv: ---------- ---------- ----------

                                Minimum:   .2400       4.800      .2664

                                Maximum:   .2400       4.800      .2664
```

```
                              COMPOSITES LABORATORY
                              NAVAL POSTGRADUATE SCHOOL
                              MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (5 CM)



Test type:       Yarn/Fiber                               Instron Corporation
                                                          Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                                 Test Date: September  9,1988

Sample Identification: 090907                             Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):   3.33                        Humidity ( % ):    50
     Crosshead Speed (mm/min ):     .500                  Temperature (deg. F):    73


'BATCH ID'          090907
'OIL OR NO OIL'     NO OIL

Dimensions:
                              Spec. 1

    Lin. Density (tex)      2036.0
    Gauge length (mm)         50.000

Out of  1 specimens,  0 excluded.
Sample comments: SAMPLE SLIPPED AT END OF TEST  TEST STOPPED BY OPERATOR

                              Displcment   % Strain    Load
                                  at          at         at
                   Specimen    Maximum     Maximum    Maximum
                   Number        (mm)        (%)        (KN)
                   ---------------------------------------------
                       1       .6500       1.300      .2026


                   Mean:       .6500       1.300      .2026

                   Standard
                   Deviation:  ----------  ---------- ----------


                   Mean -
                   2.00 * Sdv: ----------  ---------- ----------

                   Mean +
                   2.00 * Sdv: ----------  ---------- ----------

                   Minimum:    .6500       1.300      .2026

                   Maximum:    .6500       1.300      .2026
```

```
                         COMPOSITES LABORATORY
                         NAVAL POSTGRADUATE SCHOOL
                         MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (5 CM)


Test type:      Yarn/Fiber                              Instron Corporation
                                                        Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                               Test Date: September  9,1988

Sample Identification: 090908                           Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):   3.33                      Humidity ( % ):    50
     Crosshead Speed (mm/min ):    .500                 Temperature (deg. F):    73


'BATCH ID'          090908
'OIL OR NO OIL'     NO OIL

Dimensions:
                                Spec. 1

    Lin. Density (tex)        2036.0
    Gauge length (mm)           50.000

Out of  1 specimens,  0 excluded.

                              Displcment  % Strain     Load
                                 at          at         at
                     Specimen  Maximum    Maximum    Maximum
                     Number     (mm)        (%)       (KN)
                     ---------------------------------------------
                         1     .6400       1.280      .2299


                     Mean:     .6400       1.280      .2299

                     Standard
                     Deviation: ----------  ----------  ----------


                     Mean -
                     2.00 * Sdv: ----------  ----------  ----------

                     Mean +
                     2.00 * Sdv: ----------  ----------  ----------

                     Minimum:   .6400       1.280      .2299

                     Maximum:   .6400       1.280      .2299
```

```
 VERSION  4.01c
    Sample id : 090908                          Test date : September  9,1988
      Version : 4.01c                        Version date : 06/09/88
Report file# : 12                                 Operator : Mark Jones

X conversion :    .03937008                  X A/D offset :           .0000
Y conversion :   2.20462300                  Y A/D offset :           .0000

 Sample rate :    3.33                       Extensometer : NO
   A/D range :    0                             Autostart : OFF
  Calib type : AUTOMATIC                         Geometry : CYLINDRICAL
  Calib load :       110.2311                Calib extens :           .0000
 Temperature :   73                              Humidity : 50
   Test type : DENIER                         # specimens :   1
    Bar type : AS-4                          Entry dimens : YES
 Break check :     10.00000                  Thresh delay :       .22481
  Load limit :    112.40450                  Extens limit :       .09843

Sample dimensions :
A:       .0394   B: 18324.0000    C:      1.9685    D:       .0394    E: NO
---------------------------------------------------------------------------
   Specimen # :        1                     Test end status :    10
Maximum load :       51.608                  Max load point #  :          256
   Max extens :         .044                 Max extens pnt #  :          450

Number of elements :    450

Specimen dimensions :
A:       .0393701 B: 18324.0000000 C:      1.9685040 D:       .0393701 E:NO


 Auxiliary Input Array # 1
******* ******* ******* ******* ******* ******* ******* ******* *******
 Auxiliary Input Array # 2
******* ******* ******* ******* ******* ******* ******* *******      .04
---------------------------------------------------------------------------
```

```
                          COMPOSITES LABORATORY
                          NAVAL POSTGRADUATE SCHOOL
                          MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (5 CM)


Test type:      Yarn/Fiber                            Instron Corporation
                                                      Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                             Test Date: September  9,1988

Sample Identification: 090909                         Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):   3.33                    Humidity ( % ):    50
     Crosshead Speed (mm/min ):    .500               Temperature (deg. F):    73


'BATCH ID'          090909
'OIL OR NO OIL'     OIL

Dimensions:
                                 Spec. 1

    Lin. Density (tex)         2036.0
    Gauge length (mm)            50.000

Out of  1 specimens,  0 excluded.
Sample comments: OIL SAMPLE

                                 Displcment  % Strain     Load
                                     at         at         at
                          Specimen Maximum    Maximum    Maximum
                          Number     (mm)       (%)        (kN)
                          ---------------------------------------------
                              1     .6500     1.300      .2374


                          Mean:     .6500     1.300      .2374

                          Standard
                          Deviation: ---------- ---------- ----------


                          Mean -
                          2.00 * Sdv: ---------- ---------- ----------

                          Mean +
                          2.00 * Sdv: ---------- ---------- ----------

                          Minimum:   .6500     1.300      .2374

                          Maximum:   .6500     1.300      .2374
```

```
VERSION  4.01c
   Sample id : 090909                        Test date : September  9,1988
     Version : 4.01c                      Version date : 06/09/88
 Report file# : 12                            Operator : Mark Jones

X conversion :   .03937008                X A/D offset :            .0000
Y conversion :  2.20462300                Y A/D offset :            .0000

 Sample rate :    3.33                    Extensometer : NO
   A/D range :    0                          Autostart : OFF
  Calib type : AUTOMATIC                      Geometry : CYLINDRICAL
  Calib load :        110.2311            Calib extens :          .0000
 Temperature :  73                            Humidity : 50
   Test type : DENIER                     # specimens  :   1
    Bar type : AS-4                       Entry dimens : YES
 Break check :     10.00000               Thresh delay :        .22481
  Load limit :    112.40450               Extens limit :        .09843

Sample dimensions  :
A:        .0394    B: 18324.0000    C:      1.9685    D:        .0394    E: NO
------------------------------------------------------------------------------
   Specimen # :        1                  Test end status :    10
 Maximum load :       53.295              Max load point #   :          261
   Max extens :         .059              Max extens pnt #   :          603

 Number of elements :    603

 Specimen dimensions  :
A:       .0393701 B: 18324.0000000 C:      1.9685040 D:       .0393701 E:NO


 Auxiliary Input Array # 1
******* ******* ******* ******* ******* ******* ******* ******* *******
 Auxiliary Input Array # 2
******* ******* ******* ******* ******* ******* ******* ******* *******
-------------------------------------------------------------------------------
```

```
                                COMPOSITES LABORATORY
                                NAVAL POSTGRADUATE SCHOOL
                                MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (2.5 CM)



Test type:      Yarn/Fiber                                 Instron Corporation
                                                           Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                                  Test Date: September  9,1988

Sample Identification: 090910                              Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):   1.67                         Humidity ( % ):    50
     Crosshead Speed (mm/min ):    .250                    Temperature (deg. F):    73


'BATCH 10'          090910
'OIL OR NO OIL'     NO OIL

Dimensions:
                                 Spec. 1

    Lin. Density (tex)         2036.0
    Gauge length (mm)            25.000

Out of  1 specimens,  0 excluded.

                                  Displcment  % Strain    Load
                                     at          at        at
                             Specimen   Maximum    Maximum   Maximum
                             Number      (mm)       (%)       (kN)
                             ---------------------------------------------
                                1       .4600      1.840     .2174


                             Mean:      .4600      1.840     .2174

                             Standard
                             Deviation: ---------- ---------- ----------


                             Mean -
                             2.00 * Sdv: ---------- ---------- ----------

                             Mean +
                             2.00 * Sdv: ---------- ---------- ----------

                             Minimum:   .4600      1.840     .2174

                             Maximum:   .4600      1.840     .2174
```

```
                     COMPOSITES LABORATORY
                     NAVAL POSTGRADUATE SCHOOL
                     MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (2.5 CM)


Test type:      Yarn/Fiber                           Instron Corporation
                                                     Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                            Test Date: September 10,1988

Sample Identification: 100901                        Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):   1.67                   Humidity ( % ):    50
     Crosshead Speed (mm/min ):    .250              Temperature (deg. F):    73


'BATCH ID'          100901
'OIL OR NO OIL'     NO OIL

Dimensions:
                              Spec. 1

    Lin. Density (tex)       2036.0
    Gauge length (mm)          25.000

Out of  1 specimens,  0 excluded.

                              Displcment  % Strain    Load
                                  at         at         at
                      Specimen  Maximum    Maximum    Maximum
                      Number     (mm)        (%)       (kN)
                      --------------------------------------------
                          1     .4300      1.720      .2130


                      Mean:     .4300      1.720      .2130

                      Standard
                      Deviation: ---------- ---------- ----------


                      Mean -
                      2.00 * Sdv: ---------- ---------- ----------

                      Mean +
                      2.00 * Sdv: ---------- ---------- ----------

                      Minimum:   .4300      1.720      .2130

                      Maximum:   .4300      1.720      .2130
```

```
 VERSION  4.01c
   Sample id : 100901                            Test date : September 10,1988
     Version : 4.01c                          Version date : 06/09/88
Report file# : 14                                 Operator : Mark Jones

X conversion :    .03937008                   X A/D offset :            .0000
Y conversion :  2.20462300                    Y A/D offset :            .0000

 Sample rate :    1.67                        Extensometer : NO
   A/D range :    0                              Autostart : OFF
  Calib type : AUTOMATIC                          Geometry : CYLINDRICAL
  Calib load :       110.2311                 Calib extens :          .0000
 Temperature :   73                               Humidity : 50
   Test type : DENIER                        # specimens :    1
    Bar type : AS-4                           Entry dimens : YES
 Break check :     10.00000                   Thresh delay :      1.12404
  Load limit :    112.40450                   Extens limit :       .04921

Sample dimensions :
A:        .0394    B: 18324.0000    C:        .9843    D:        .0394    E: NO
------------------------------------------------------------------------------
  Specimen # :       1                        Test end status :    10
Maximum load :      47.850                    Max load point #  :          180
  Max extens :         .029                   Max extens pnt #  :          305

Number of elements :    305

Specimen dimensions :
A:        .0393701 B: 18324.0000000 C:        .9842520 D:        .0393701 E:NO

 Auxiliary Input Array # 1
******* ******* ******* ******* ******* ******* ******* ******* *******
 Auxiliary Input Array # 2
******* ******* ******* ******* ******* ******* ******* ******* *******
------------------------------------------------------------------------------
```

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                        COMPOSITES LABORATORY
                        NAVAL POSTGRADUATE SCHOOL
                        MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (2.5 CM)


Test type:      Yarn/Fiber                                 Instron Corporation
                                                           Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                                  Test Date: September 10,1988

Sample Identification: 100902                              Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):   1.67                         Humidity ( % ):    50
     Crosshead Speed (mm/min ):    .250                    Temperature (deg. F):    73


'BATCH ID'          100902
'OIL OR NO OIL'     OIL

Dimensions:
                                Spec. 1

    Lin. Density (tex)        2036.0
    Gauge length (mm)           25.000

Out of  1 specimens,  0 excluded.
Sample comments: SAMPLE APPEARED TO SLIP

                               Displcment   % Strain      Load
                                   at          at          at
                     Specimen   Maximum     Maximum     Maximum
                     Number      (mm)         (%)        (kN)
                     ---------------------------------------------
                        1       .5000       2.000       .1922


                     Mean:      .5000       2.000       .1922

                     Standard
                     Deviation: ----------  ----------  ----------


                     Mean -
                     2.00 * Sdv: ----------  ----------  ----------

                     Mean +
                     2.00 * Sdv: ----------  ----------  ----------

                     Minimum:   .5000       2.000       .1922

                     Maximum:   .5000       2.000       .1922
```

```
                          COMPOSITES LABORATORY
                          NAVAL POSTGRADUATE SCHOOL
                          MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (2.5 CM)


Test type:      Yarn/Fiber                                Instron Corporation
                                                          Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                                 Test Date: September 10,1988

Sample Identification: 100903                             Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):   1.67                        Humidity ( % ):    50
     Crosshead Speed (mm/min ):    .250                   Temperature (deg. F):    73


'BATCH ID'          100903
'OIL OR NO OIL'     OIL

Dimensions:
                               Spec. 1

    Lin. Density (tex)       2036.0
    Gauge length (mm)          25.000

Out of  1 specimens,  0 excluded.
Sample comments: SAMPLE SLIPPED

                              Displcment  % Strain    Load
                                  at         at        at
                  Specimen     Maximum    Maximum    Maximum
                  Number         (mm)       (%)       (KN)
                  --------------------------------------------
                      1        .4300      1.720      .2051


                  Mean:        .4300      1.720      .2051

                  Standard
                  Deviation:  ---------- ---------- ----------


                  Mean -
                  2.00 * Sdv: ---------- ---------- ----------

                  Mean +
                  2.00 * Sdv: ---------- ---------- ----------

                  Minimum:     .4300      1.720      .2051

                  Maximum:     .4300      1.720      .2051
```

```
                          COMPOSITES LABORATORY
                          NAVAL POSTGRADUATE SCHOOL
                          MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (50 CM)


Test type:      Yarn/Fiber                               Instron Corporation
                                                         Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                                Test Date: September 10,1988

Sample Identification: 100904                            Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):   6.67                       Humidity ( % ):    50
     Crosshead Speed (mm/min ):   5.000                  Temperature (deg. F):    73


'BATCH ID'          100904
'OIL OR NO OIL'     NO OIL

Dimensions:
                              Spec. 1

    Lin. Density (tex)       2036.0
    Gauge length (mm)          500.00

Out of  1 specimens,  0 excluded.

                             Displcment  % Strain    Load
                                 at         at        at
                          Specimen   Maximum    Maximum   Maximum
                          Number       (mm)       (%)       (KN)
                          ---------------------------------------------
                              1      3.370      .6740      .1090


                          Mean:      3.370      .6740      .1090

                          Standard
                          Deviation: ---------- ---------- ----------


                          Mean -
                          2.00 * Sdv: ---------- ---------- ----------

                          Mean +
                          2.00 * Sdv: ---------- ---------- ----------

                          Minimum:   3.370      .6740      .1090

                          Maximum:   3.370      .6740      .1090
```

```
 VERSION  4.01c
    Sample id : 100904                       Test date : September 10,1988
      Version : 4.01c                     Version date : 06/09/88
Report file# : 11                              Operator : Mark Jones

X conversion :   .03937008                X A/D offset :            .0000
Y conversion :  2.20462300                Y A/D offset :            .0000

 Sample rate :   6.67                     Extensometer : NO
   A/D range :   0                           Autostart : OFF
  Calib type : AUTOMATIC                      Geometry : CYLINDRICAL
  Calib load :      110.2311              Calib extens :          .0000
 Temperature :  73                            Humidity : 50
   Test type : DENIER                      # specimens :   1
    Bar type : AS-4                       Entry dimens : YES
 Break check :     10.00000               Thresh delay :       .22401
  Load limit :    112.40450               Extens limit :       .98425

Sample dimensions :
A:       .0394    B: 18324.0000    C:    19.6850    D:       .0394    E: NO
---------------------------------------------------------------------------
  Specimen # :       1                    Test end status :   10
Maximum load :       24.472               Max load point #   :          271
  Max extens :         .295               Max extens pnt #   :          601

Number of elements :    601

Specimen dimensions :
A:       .0393701 B: 18324.0000000 C:     19.6850400 D:       .0393701 E:NO


Auxiliary Input Array # 1
******* ******* ******* ******* ******* ******* ******* ******* *******
Auxiliary Input Array # 2
******* ******* ******* ******* ******* ******* ******* ******* *******
---------------------------------------------------------------------------
```

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                            COMPOSITES LABORATORY
                            NAVAL POSTGRADUATE SCHOOL
                            MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (50 CM)



Test type:      Yarn/Fiber                            Instron Corporation
                                                      Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                             Test Date: September 10,1988

Sample Identification: 100905                         Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):   6.67                    Humidity ( % ):    50
     Crosshead Speed (mm/min ):   5.000               Temperature (deg. F):    73


'BATCH ID'          100905
'OIL OR NO OIL'     OIL

Dimensions:
                                Spec. 1

    Lin. Density (tex)        2036.0
    Gauge length (mm)           500.00

Out of  1 specimens,  0 excluded.
Sample comments: OIL SAMPLE

                              Displcment  % Strain     Load
                                  at         at         at
                    Specimen   Maximum    Maximum    Maximum
                    Number       (mm)       (%)        (KN)
                    --------------------------------------------
                        1      3.910      .7820      .1399


                    Mean:      3.910      .7820      .1399

                    Standard
                    Deviation: ---------- ---------- ----------


                    Mean -
                    2.00 * Sdv: ---------- ---------- ----------

                    Mean +
                    2.00 * Sdv: ---------- ---------- ----------

                    Minimum:    3.910      .7820      .1399

                    Maximum:    3.910      .7820      .1399
```

```
 VERSION  4.01c
   Sample id : 100905                         Test date : September 10,1988
     Version : 4.01c                       Version date : 06/09/88
Report file# : 11                              Operator : Mark Jones

X conversion :   .03937008                 X A/D offset :           .0000
Y conversion :  2.20462300                 Y A/D offset :           .0000

 Sample rate :   6.67                      Extensometer : NO
   A/D range :   0                            Autostart : OFF
  Calib type : AUTOMATIC                       Geometry : CYLINDRICAL
  Calib load :       110.2311              Calib extens :           .0000
 Temperature :  73                             Humidity : 50
   Test type : DENIER                       # specimens :   1
    Bar type : AS-4                        Entry dimens : YES
 Break check :     10.00000                Thresh delay :       .22481
  Load limit :    112.40450                Extens limit :       .98425

Sample dimensions :
A:        .0394   B: 18324.0000   C:     19.6850   D:       .0394   E: NO
---------------------------------------------------------------------------
  Specimen # :       1                    Test end status :   10
Maximum load :      31.471                Max load point #  :         314
  Max extens :        .316                Max extens pnt #  :         644

Number of elements :   644

Specimen dimensions :
A:       .0393701 B: 18324.0000000 C:    19.6850400 D:       .0393701 E:NO

 Auxiliary Input Array # 1
******* ******* ******* ******* ******* ******* ******* ******* *******
 Auxiliary Input Array # 2
******* ******* ******* ******* ******* ******* ******* ******* *******
---------------------------------------------------------------------------
```

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                          COMPOSITES LABORATORY
                          NAVAL POSTGRADUATE SCHOOL
                          MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (50 CM)


Test type:      Yarn/Fiber                                 Instron Corporation
                                                           Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                                  Test Date: September 10,1988

Sample Identification: 100906                              Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):   6.67                         Humidity ( % ):    50
     Crosshead Speed (mm/min ):   5.000                    Temperature (deg. F):    73


'BATCH ID'          100906
'OIL OR NO OIL'     OIL

Dimensions:
                                Spec. 1

    Lin. Density (tex)        2036.0
    Gauge length (mm)           500.00

Out of  1 specimens,  0 excluded.

                                Displcment   % Strain     Load
                                    at          at          at
                     Specimen    Maximum     Maximum     Maximum
                     Number        (mm)        (%)         (KN)
                     ---------------------------------------------
                         1       3.660       .7320       .1329


                     Mean:       3.660       .7320       .1329

                     Standard
                     Deviation:  ----------  ----------  ----------


                     Mean -
                     2.00 * Sdv: ----------  ----------  ----------

                     Mean +
                     2.00 * Sdv: ----------  ----------  ----------

                     Minimum:    3.660       .7320       .1329

                     Maximum:    3.660       .7320       .1329
```

```
                              COMPOSITES LABORATORY
                              NAVAL POSTGRADUATE SCHOOL
                              MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (25.0 CM)


Test type:      Yarn/Fiber                                 Instron Corporation
                                                           Series IX Automated Materials Testing System v4.01c
Operator name: Mark Jones                                  Test Date: September 10,1988

Sample Identification: 100907                              Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
     Sample Rate (pts/sec):   5.00                         Humidity ( % ):    50
     Crosshead Speed (mm/min ):   2.500                    Temperature (deg. F):    73


'BATCH ID'           100907
'OIL OR NO OIL'      OIL

Dimensions:
                                Spec. 1

    Lin. Density (tex)        2036.0
    Gauge length (mm)           250.00

Out of  1 specimens,  0 excluded.

                               Displcment   % Strain     Load
                                   at          at          at
                     Specimen   Maximum     Maximum     Maximum
                     Number       (mm)        (%)        (kN)
                     ---------------------------------------------
                         1      2.370       .9480       .1718


                     Mean:      2.370       .9480       .1718

                     Standard
                     Deviation: ----------  ----------  ----------


                     Mean -
                     2.00 * Sdv: ---------- ----------  ----------

                     Mean +
                     2.00 * Sdv: ---------- ----------  ----------

                     Minimum:   2.370       .9480       .1718

                     Maximum:   2.370       .9480       .1718
```

```
 VERSION  4.01c
    Sample id : 100907                          Test date : September 10,1988
      Version : 4.01c                        Version date : 06/09/88
 Report file# : 15                               Operator : Mark Jones

 X conversion :    .03937008                 X A/D offset :          .0000
 Y conversion :   2.20462300                 Y A/D offset :          .0000

  Sample rate :    5.00                      Extensometer : NO
    A/D range :    0                            Autostart : OFF
   Calib type : AUTOMATIC                        Geometry : CYLINDRICAL
   Calib load :        110.2311              Calib extens :          .0000
  Temperature :  73                              Humidity : 50
    Test type : DENIER                        # specimens :   1
     Bar type : AS-4                         Entry dimens : YES
  Break check :      10.00000                Thresh delay :       .22481
   Load limit :     112.40450                Extens limit :       .49213

 Sample dimensions :
 A:        .0394    B: 18324.0000    C:      9.8425    D:        .0394    E: NO
------------------------------------------------------------------------------
   Specimen # :        1                     Test end status :    10
 Maximum load :       38.573                 Max load point #  :           285
   Max extens :         .179                 Max extens pnt #  :           547

 Number of elements :    547

 Specimen dimensions :
A:       .0393701 B: 18324.0000000 C:      9.8425200 D:       .0393701 E:NO


 Auxiliary Input Array # 1
******* ******* ******* ******* ******* ******* ******* ******* *******
 Auxiliary Input Array # 2
******* ******* ******* ******* ******* ******* ******* ******* *******
------------------------------------------------------------------------------
```

```
                              COMPOSITES LABORATORY
                              NAVAL POSTGRADUATE SCHOOL
                              MONTEREY  CA  93940

GRAPHITE BUNDLE TEST (25.0 CM)



Test type:      Yarn/Fiber                                 Instron Corporation
                                                           Series IX Automated Materials Testing System v4.01c
Operator name: joe                                         Test Date: September 10,1988

Sample Identification: 100908                              Sample Type:   AS-4
Interface Type: 4200 Series
Machine Parameters of test:
    Sample Rate (pts/sec):   5.00                          Humidity ( % ):    50
    Crosshead Speed (mm/min ):   2.500                     Temperature (deg. F):    73


'BATCH ID'          100908
'OIL OR NO OIL'     NO OIL

Dimensions:
                              Spec. 1

   Lin. Density (tex)       2036.0
   Gauge length (mm)          250.00

Out of  1 specimens,  0 excluded.

                              Displcment  % Strain     Load
                                  at         at         at
                         Specimen  Maximum    Maximum    Maximum
                         Number     (mm)       (%)        (KN)
                         --------------------------------------------
                            1     2.390      .9560      .1694


                         Mean:    2.390      .9560      .1694

                         Standard
                         Deviation: ---------- ---------- ----------


                         Mean -
                         2.00 * Sdv: ---------- ---------- ----------

                         Mean +
                         2.00 * Sdv: ---------- ---------- ----------

                         Minimum:  2.390      .9560      .1694

                         Maximum:  2.390      .9560      .1694
```

```
 VERSION  4.01c
    Sample id : 100908                         Test date : September 10,1988
      Version : 4.01c                       Version date : 06/09/88
 Report file# : 15                              Operator : joe

X conversion :    .03937008                 X A/D offset :            .0000
Y conversion :   2.20462300                 Y A/D offset :            .0000

 Sample rate :    5.00                      Extensometer : NO
   A/D range :    0                            Autostart : OFF
  Calib type : AUTOMATIC                        Geometry : CYLINDRICAL
  Calib load :      110.2311                Calib extens :          .0000
 Temperature :   73                             Humidity : 50
   Test type : DENIER                        # specimens :   1
    Bar type : AS-4                         Entry dimens : YES
 Break check :     10.00000                 Thresh delay :       .22481
  Load limit :    112.40450                 Extens limit :       .49213

Sample dimensions :
A:        .0394   B: 18324.0000    C:      9.8425    D:       .0394    E: NO
------------------------------------------------------------------------------
  Specimen # :       1                      Test end status :   10
Maximum load :      38.011                  Max load point #  :          207
  Max extens :         .174                 Max extens pnt #  :          530

Number of elements :   530

Specimen dimensions :
A:        .0393701 B: 18324.0000000 C:      9.8425200 D:       .0393701 E:NO


 Auxiliary Input Array # 1
******* ******* ******* ******* ******* ******* ******* ******* *******
 Auxiliary Input Array # 2
******* ******* ******* ******* ******* ******* ******* *******      .10
------------------------------------------------------------------------------
```

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